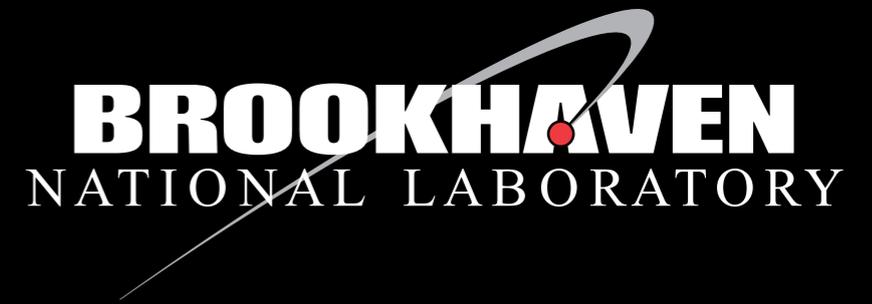




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Moving forward to constrain the shear and bulk viscosity of QCD

Björn Schenke, Brookhaven National Laboratory
in collaboration with *Gabriel Denicol (BNL), Akihiko Monnai (RBRC)*

January 22 2016

RBRC workshop: *Opportunities for Exploring
Longitudinal Dynamics in Heavy Ion Collisions at RHIC*
Brookhaven National Laboratory

Introduction

New developments are needed to describe full 3D structure and lower energy heavy ion collisions

- Net-baryon current ✓
- Equation of state at finite baryon chemical potential ✓
- Initial state with fluctuating baryon- and entropy-density ✓
- Fluctuations in all three spatial dimensions ✓
- Baryon diffusion (to do)
- Strangeness and electric currents (to do)

Will show

- momentum and rapidity distributions at different energies
- rapidity dependent flow and the effect of $(\eta/s)(T)$
- two-particle pseudo rapidity correlations (of $h^{+/-}$ and net-baryons)

Hydrodynamics

Use the state of the art 3+1D viscous relativistic hydrodynamics **MUSIC** with **shear** and **bulk** viscosity and all nonlinear terms that couple bulk viscous pressure and shear-stress tensor

Solve $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu J_B^\mu = 0$ along with

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\overset{\text{bulk}}{\pi^{\mu\nu}}\overset{\text{shear}}{\sigma_{\mu\nu}}$$

$$\tau_\pi \dot{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

The transport coefficients τ_Π , $\delta_{\Pi\Pi}$, $\lambda_{\Pi\pi}$, τ_π , $\delta_{\pi\pi}$, ϕ_7 , $\tau_{\pi\pi}$, $\lambda_{\pi\Pi}$ are fixed using formulas derived

from the Boltzmann equation near the conformal limit

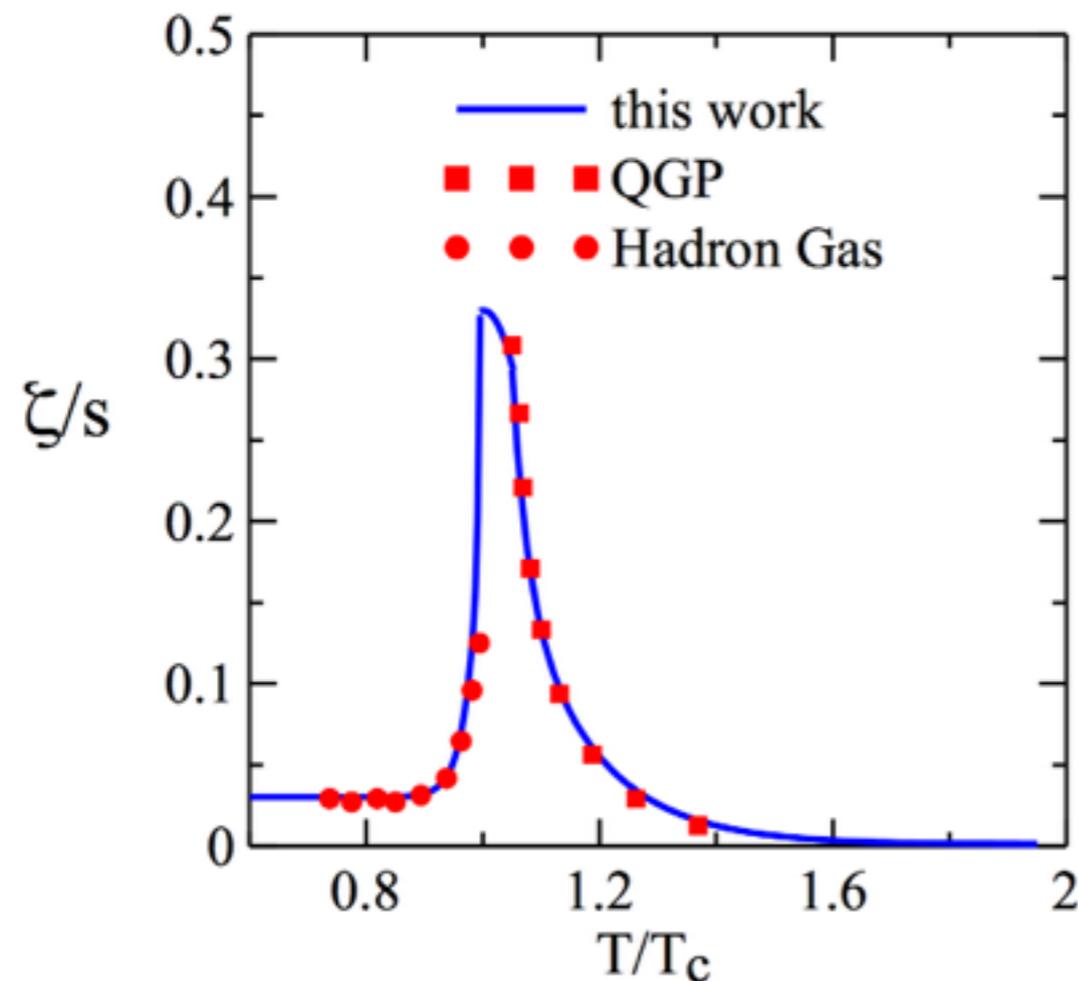
G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. C 90, 024912 (2014)

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

Viscosities

In the calculations presented here we use:

- shear viscosity (constant or with T dependence to be defined)
- bulk viscosity:



S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale
Phys.Rev.Lett. 115 (2015) 13, 132301

G. S. Denicol, U. W. Heinz, M. Martinez, J. Noronha and M. Strickland,
Phys. Rev. D 90, 125026 (2014);
Phys. Rev. Lett. 113, 202301 (2014)

QGP: F. Karsch, D. Kharzeev and K. Tuchin,
Phys. Lett. B 663, 217 (2008)

Hadron Gas:

J. Noronha-Hostler, J. Noronha and C. Greiner,
Phys. Rev. Lett. 103, 172302 (2009)

Constructing the equation of state (EoS)

Taylor Expansion

Cannot deal with complex Fermion determinants on lattice, so Taylor expand around zero baryon chemical potential

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \frac{1}{2} \chi_B^{(2)} \left(\frac{\mu_B}{T} \right)^2 + \frac{1}{4!} \chi_B^{(4)} \left(\frac{\mu_B}{T} \right)^4 + \mathcal{O} \left[\left(\frac{\mu_B}{T} \right)^6 \right]$$

because of matter-anti-matter symmetry only even powers appear similarly for energy density and entropy density

For net-baryon density we have

$$\frac{n_B}{T^3} = 0 + \chi_B^{(2)} \frac{\mu_B}{T} + \frac{1}{3!} \chi_B^{(4)} \left(\frac{\mu_B}{T} \right)^3 + \mathcal{O} \left[\left(\frac{\mu_B}{T} \right)^5 \right]$$

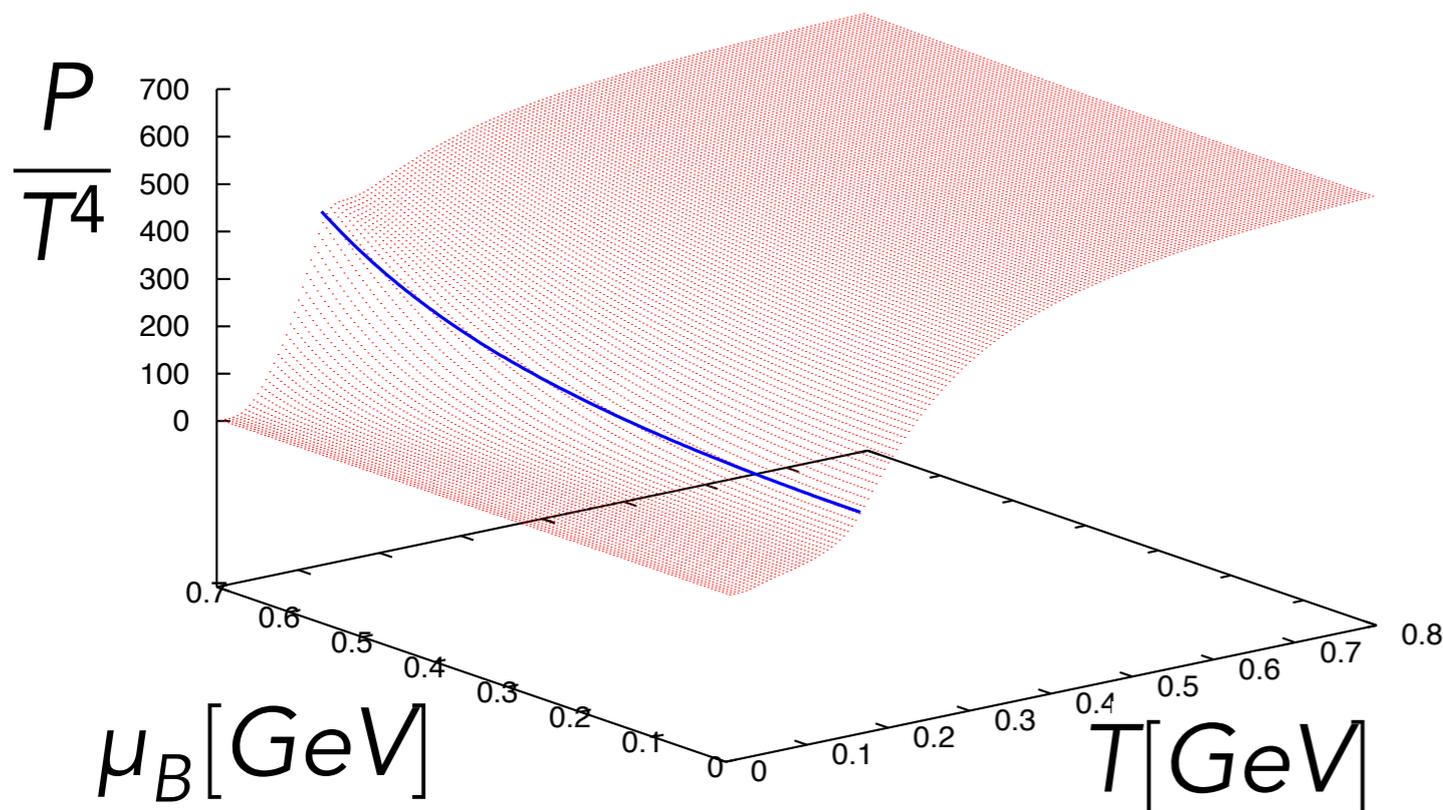
Constructing the equation of state (EoS)

Smooth matching (cross over)

We match the HRG and lattice EoS smoothly

$$\frac{P}{T^4} = \frac{1}{2} \left[1 - \tanh \frac{T - T_C(\mu_B)}{\Delta T_C} \right] \frac{P_{\text{HRG}}(T)}{T^4} + \frac{1}{2} \left[1 + \tanh \frac{T - T_C(\mu_B)}{\Delta T_C} \right] \frac{P_{\text{lat}}(T_s)}{T_s^4}$$

In the future one can introduce a critical point here.



T_C : connecting temperature

ΔT_C : width of overlap area

T_s : temperature shift

$$T_s = T + d[T_C(0) - T_C(\mu_B)]$$

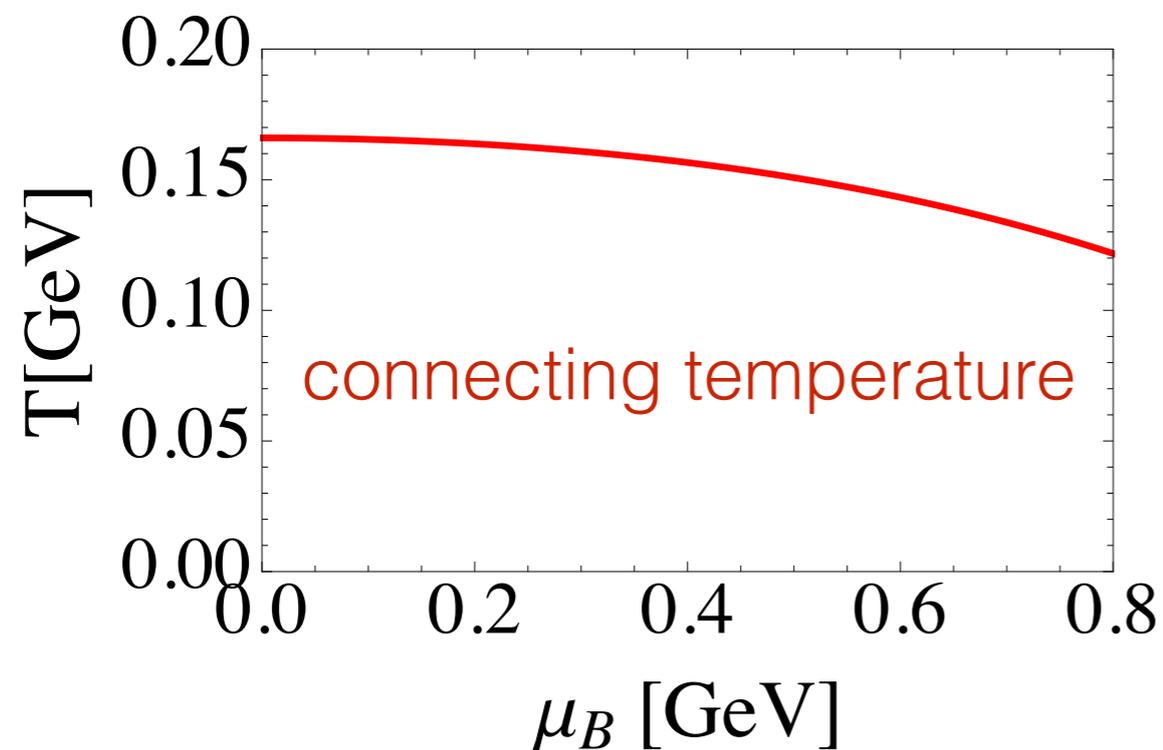
Constructing the equation of state (EoS)

Smooth matching (cross over)

We match the HRG and lattice EoS smoothly

$$\frac{P}{T^4} = \frac{1}{2} \left[1 - \tanh \frac{T - T_C(\mu_B)}{\Delta T_C} \right] \frac{P_{\text{HRG}}(T)}{T^4} + \frac{1}{2} \left[1 + \tanh \frac{T - T_C(\mu_B)}{\Delta T_C} \right] \frac{P_{\text{lat}}(T_s)}{T_s^4}$$

$$T_C(\mu_B) = 0.166 \text{ GeV} - c(0.139 \mu_B^2 + 0.053 \mu_B^4)$$



based on the chemical freeze-out line ($c=1$)

Cleymans et al, PRC73, 034905 (2006)

For the connecting line we use $c=d=0.4$, $\Delta T_C=0.1 T_C(0)$

Constructing the equation of state (EoS)

Smooth matching (cross over)

We match the HRG and lattice EoS smoothly

$$\frac{P}{T^4} = \frac{1}{2} \left[1 - \tanh \frac{T - T_C(\mu_B)}{\Delta T_C} \right] \frac{P_{\text{HRG}}(T)}{T^4} + \frac{1}{2} \left[1 + \tanh \frac{T - T_C(\mu_B)}{\Delta T_C} \right] \frac{P_{\text{lat}}(T_s)}{T_s^4}$$

Parameters P_0^{lat} and $\chi_B^{(2)}$ are determined from the lattice:

Borsanyi et al, JHEP1011, 077 (2010)

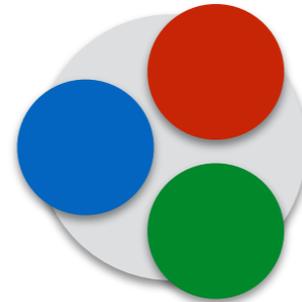
Borsanyi et al, JHEP1201, 138 (2012)

$\chi_B^{(4)}$ is obtained from the ratio $\chi_B^{(4)}/\chi_B^{(2)}$ in a HRG and parton gas model

Initial conditions - 3DMC-Glauber with quarks

Introduce a **simple** extension of the Monte Carlo Glauber model

We use **constituent quarks**



Constituent quark initial positions in the transverse plane are sampled from a 2D exponential distribution around the nucleon center (Nucleons are sampled from Woods-Saxon)

Their rapidities are sampled from nuclear parton distribution functions (in this talk we will use CTEQ10 and EPS09)

Their cross sections can be determined geometrically to reproduce the nucleon-nucleon cross sections

Event-by-event baryon density

Transverse distribution:

Implement black disk and Gaussian wounding to determine wounded quarks

Longitudinal distribution:

Implement an MC version of the **Lexus** model

S. Jeon and J. Kapusta, PRC56, 468 (1997)

Idea: Rapidity distributions in heavy ion collisions follow via linear extrapolation from p+p collisions

Distribution in p+p collisions is parametrized and fit to data

Probability for a quark with rapidity y_P to get rapidity y after collision with another quark with rapidity y_T :

$$Q(y, y_P, y_T) = \lambda \frac{\cosh(y - y_T)}{\sinh(y_P - y_T)} + (1 - \lambda) \delta(y - y_P)$$

where we treat λ as a free parameter

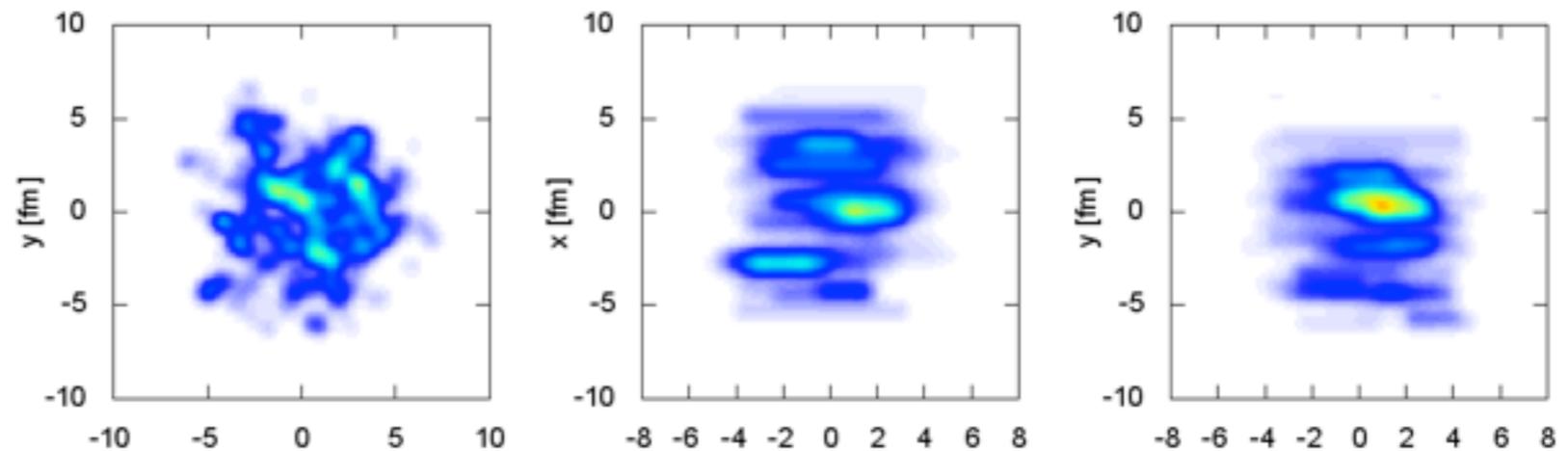
(it characterizes the stopping power for quarks)

Event-by-event baryon- and entropy density

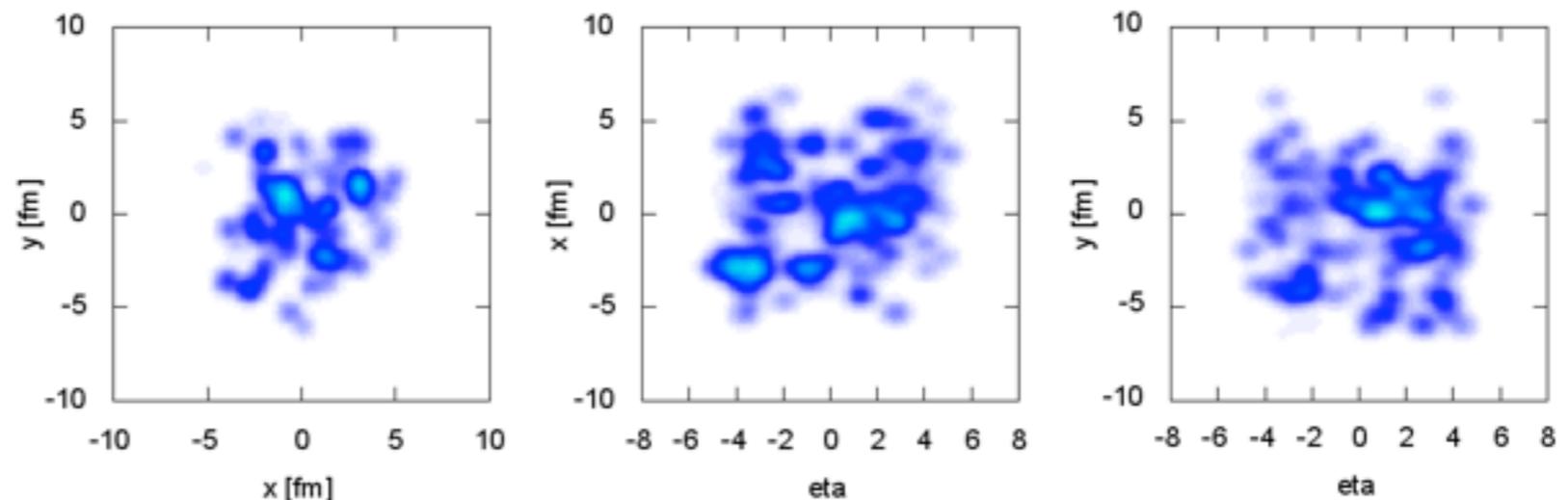
Deposit entropy density (fluctuating with NBD) between the collided constituent quarks using a Gaussian profile in the transverse plane and a constant distribution (with Gaussian edges) in rapidity

$$\sqrt{s} = 200\text{GeV}$$

energy density



baryon density



x or y [fm]

x[fm]

rapidity

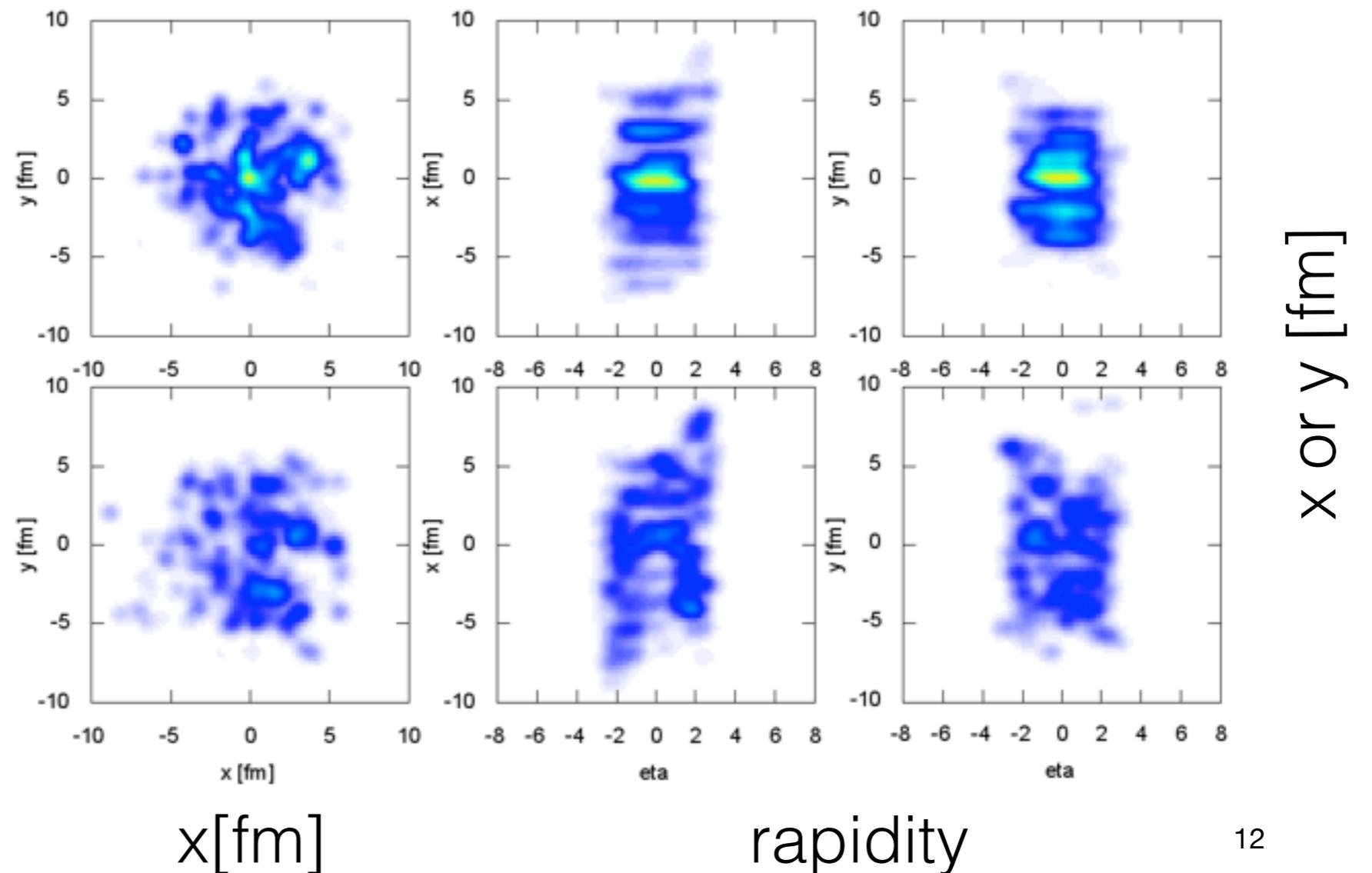
Event-by-event baryon- and entropy density

Deposit entropy density (fluctuating with NBD) between the collided constituent quarks using a Gaussian profile in the transverse plane and a constant distribution (with Gaussian edges) in rapidity

$$\sqrt{s} = 19.6 \text{ GeV}$$

energy density

baryon density

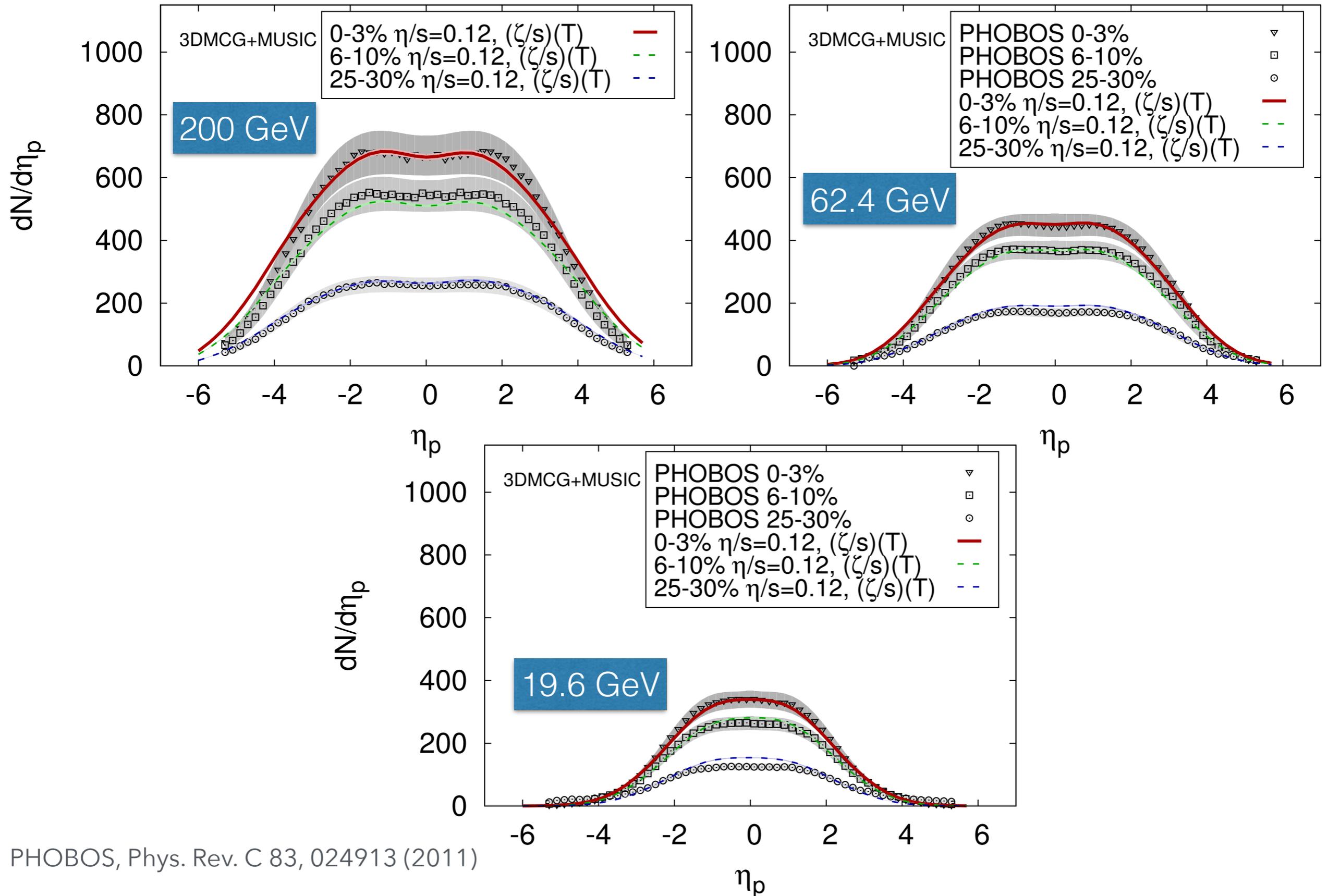


x[fm]

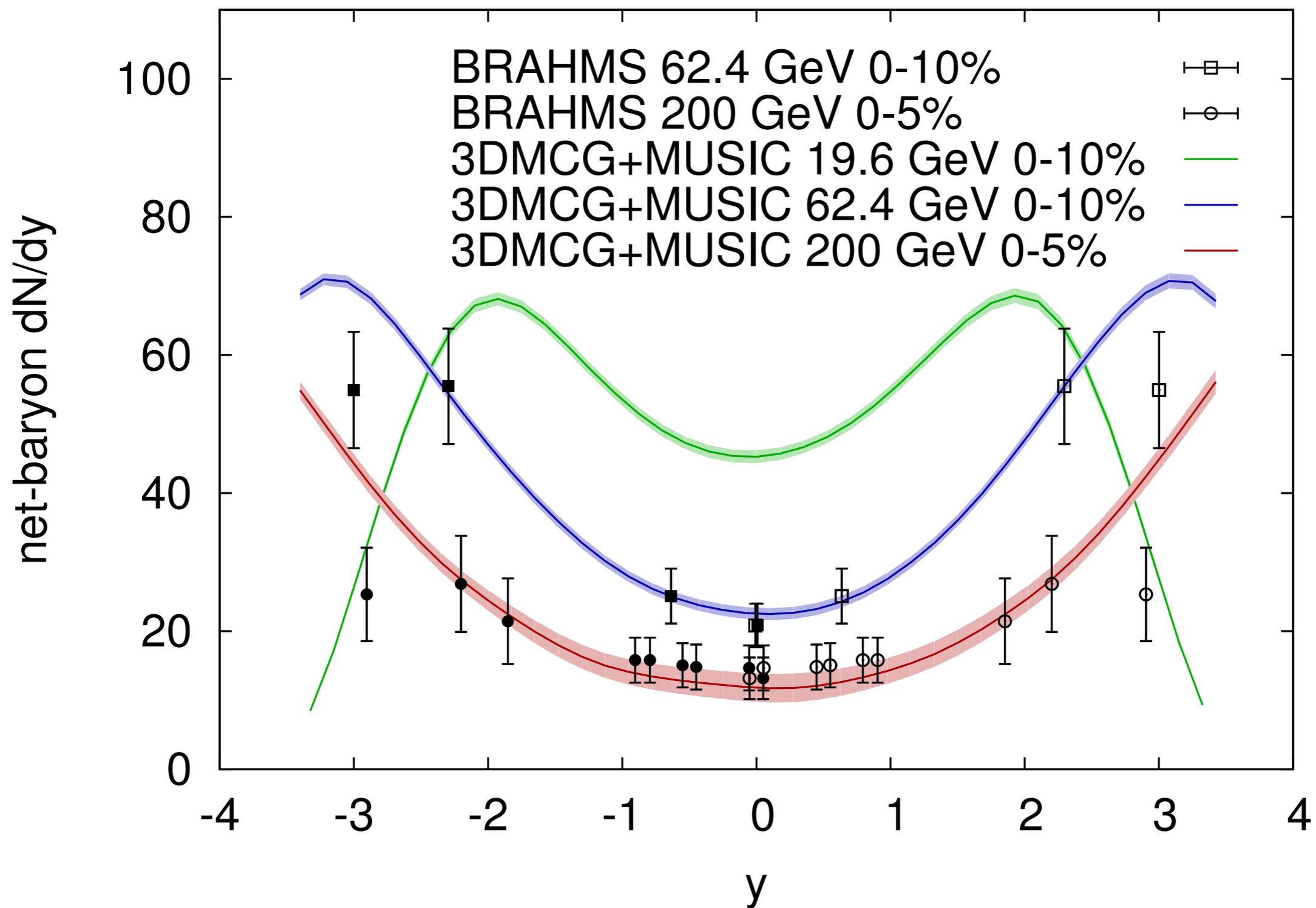
rapidity

Results

Charged hadron pseudo-rapidity distributions

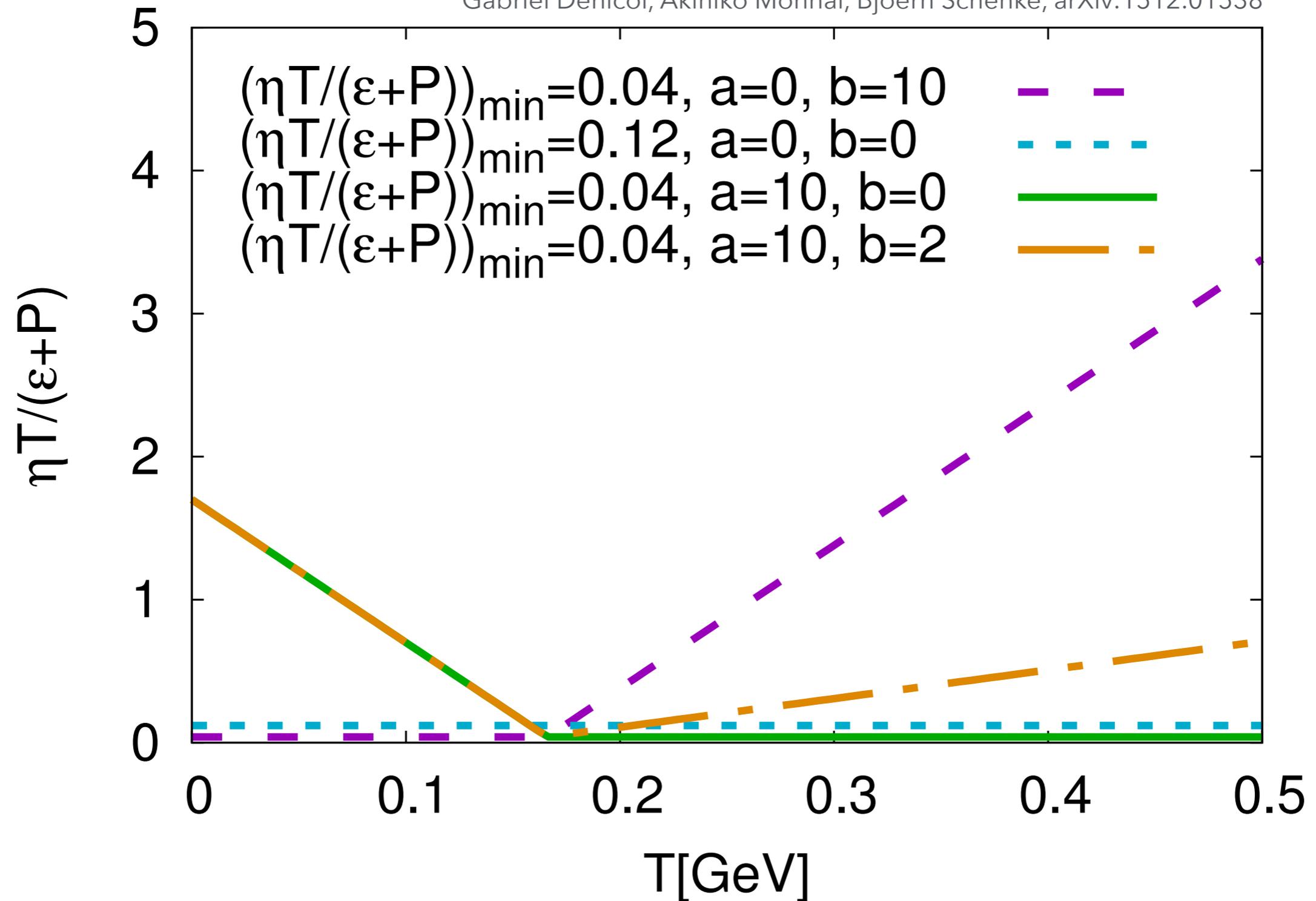


Net-baryon rapidity distributions



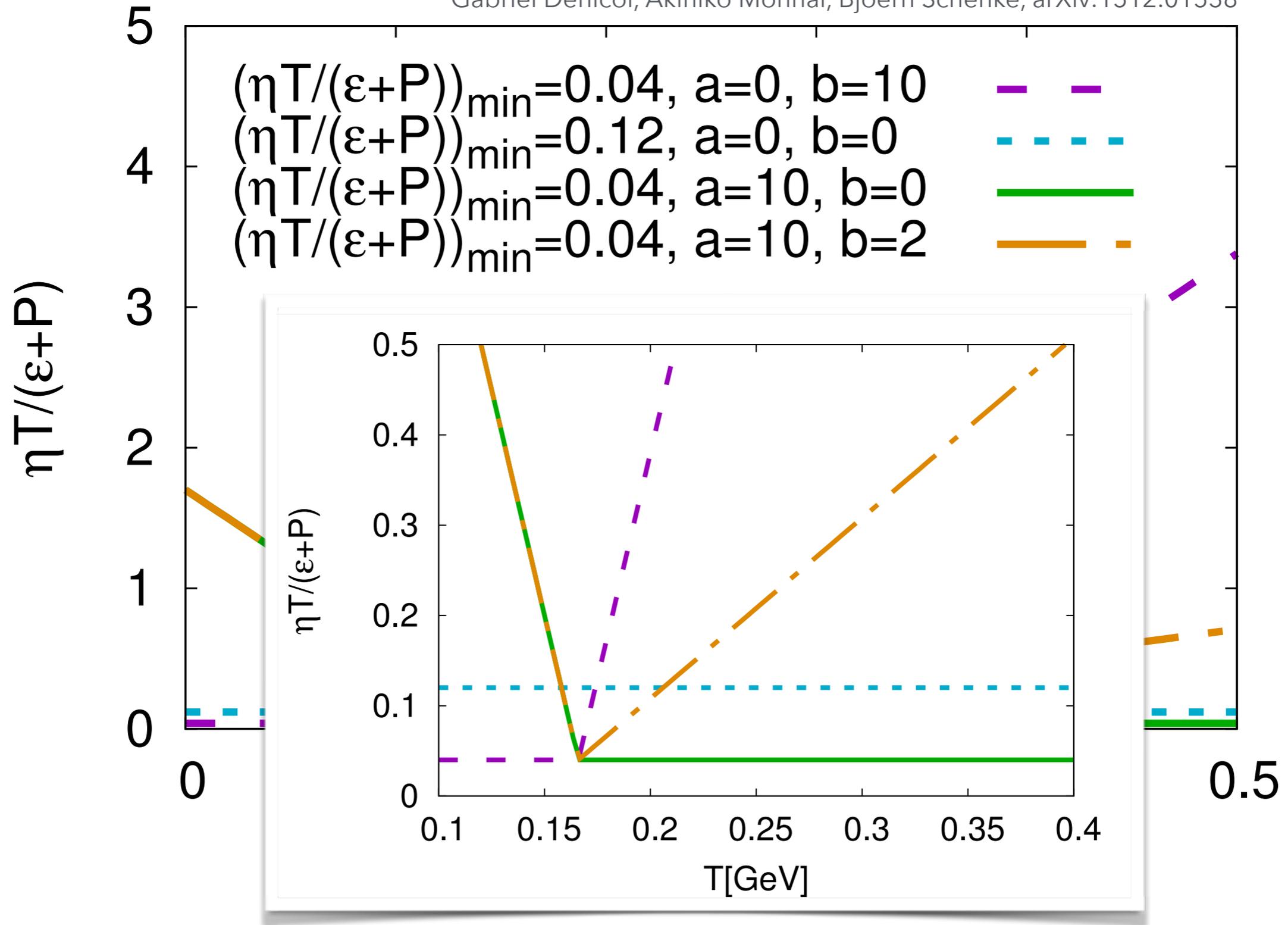
Constraining T-dependent η/s

Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538

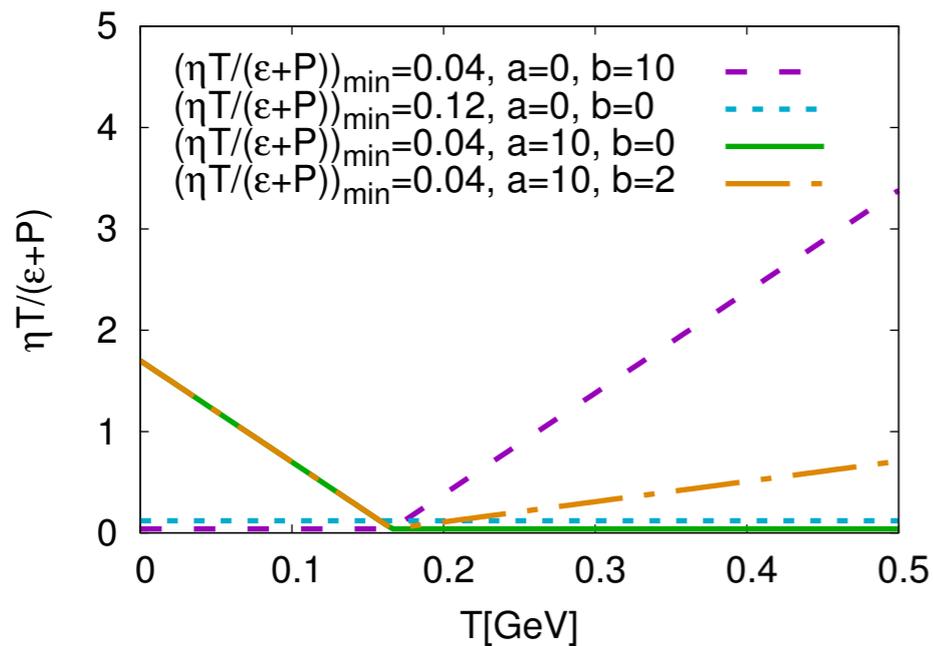


Constraining T-dependent η/s

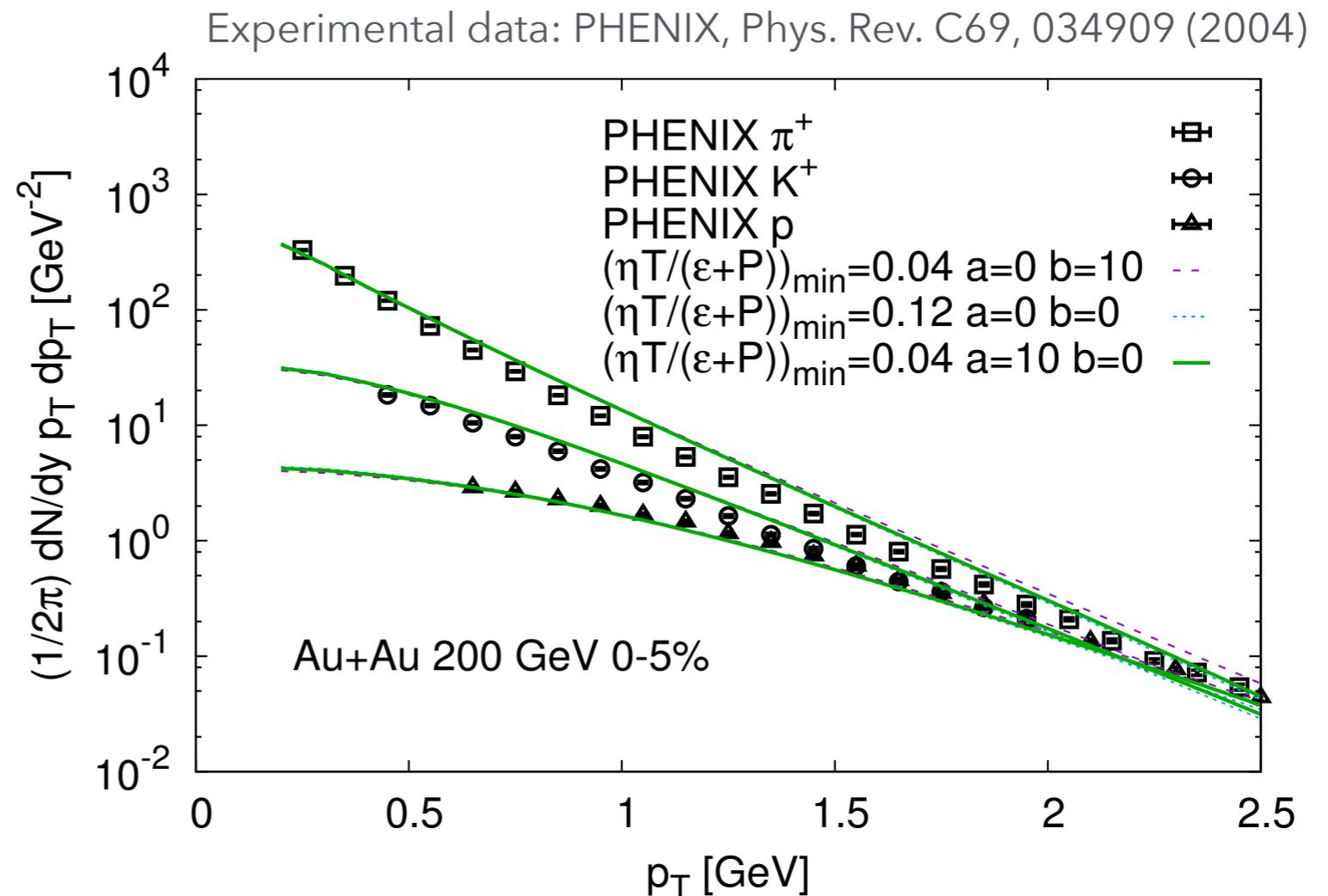
Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538



Identified particle transverse momentum spectra

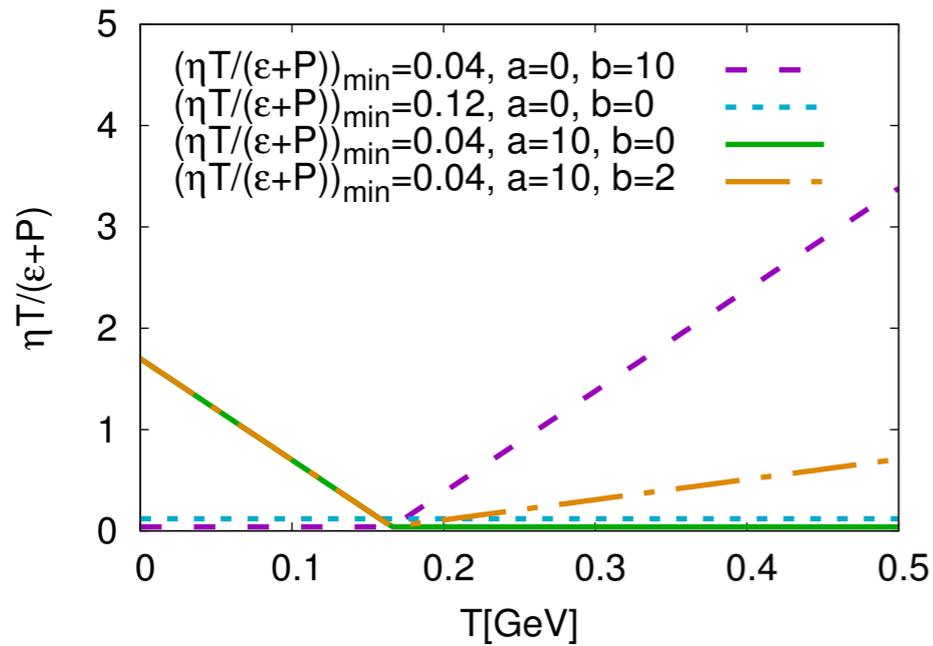


Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538



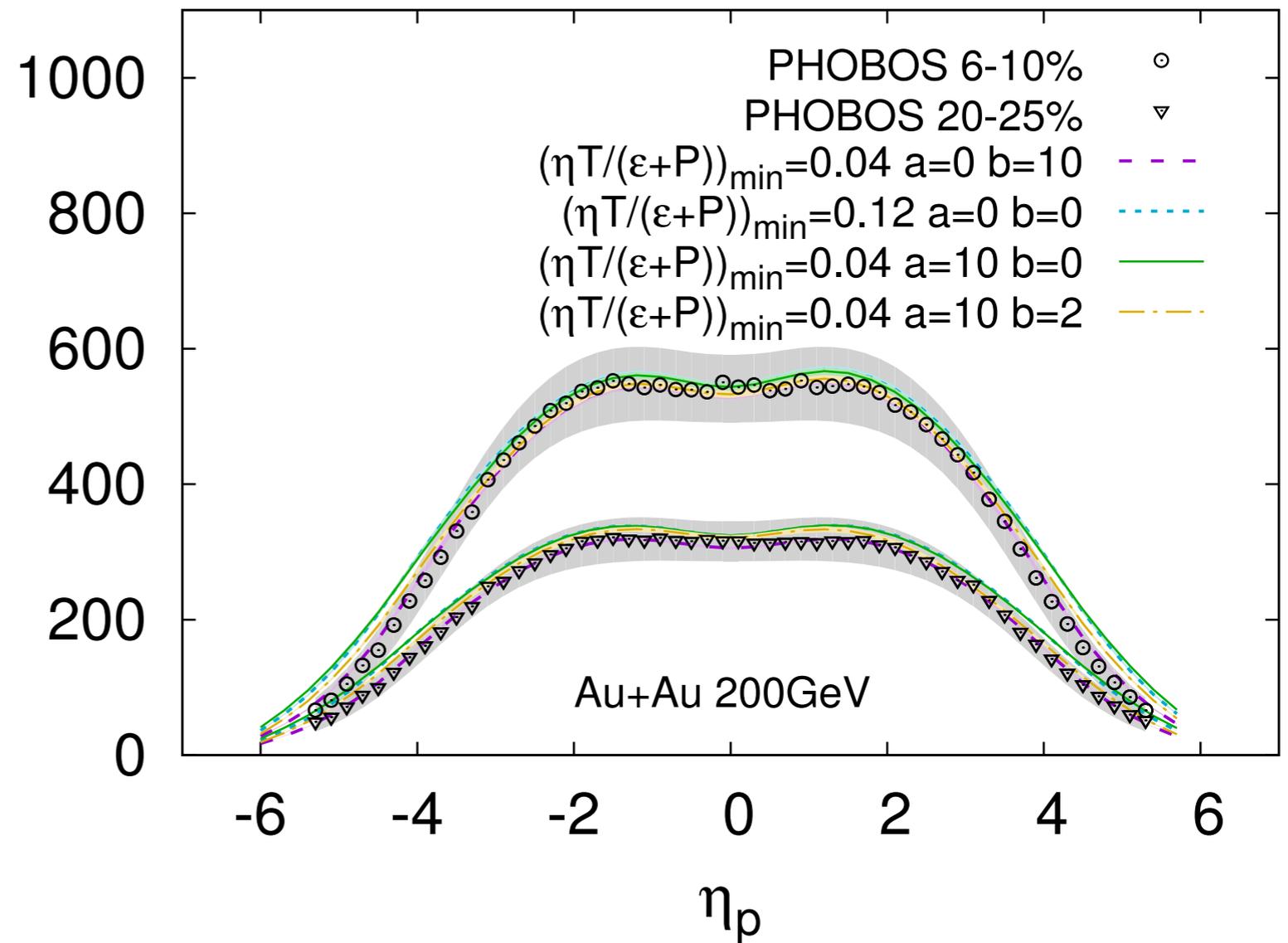
Bulk viscosity needed to get mean p_T right
 Same as with IP-Glasma initial conditions:

Charged hadron pseudo-rapidity spectra



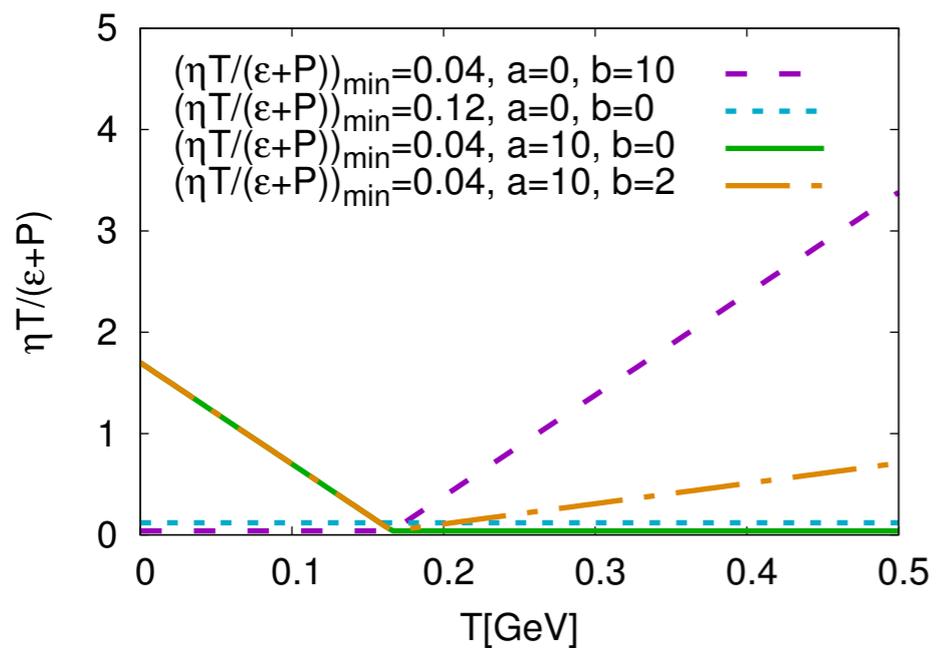
Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538

$dN/d\eta$

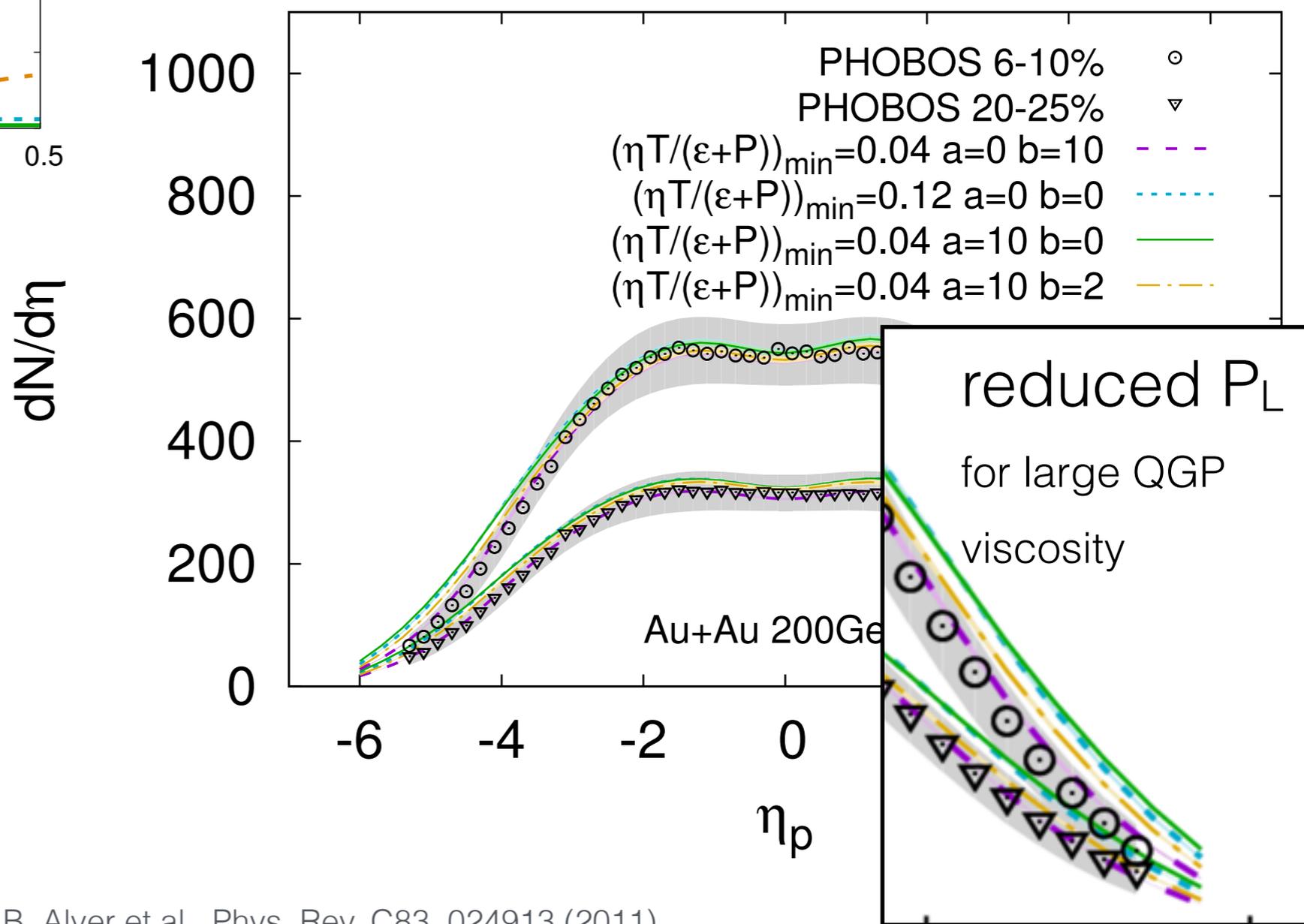


Experimental data: PHOBOS Collaboration, B. Alver et al., Phys. Rev. C83, 024913 (2011)

Charged hadron pseudo-rapidity spectra

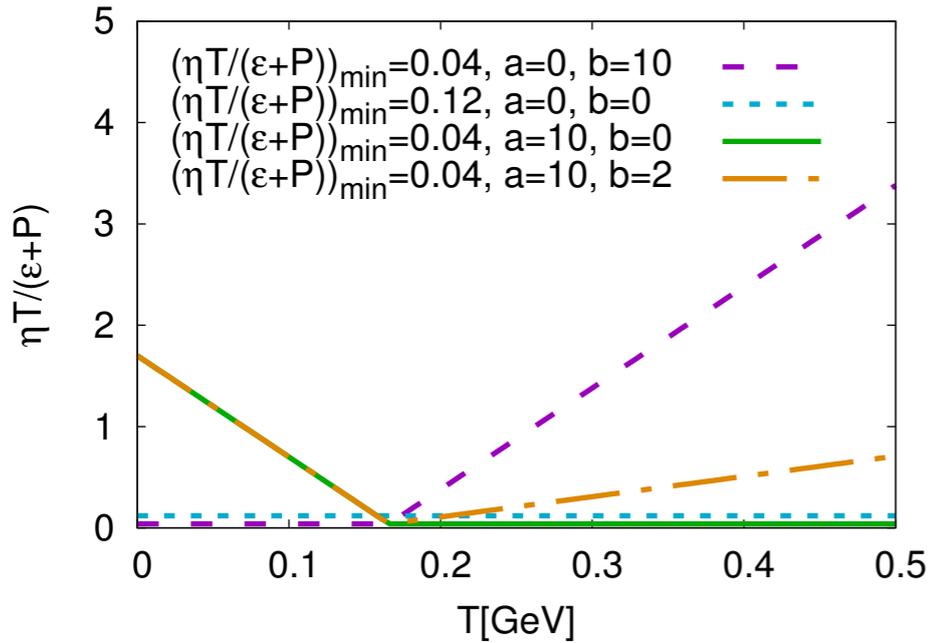


Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538



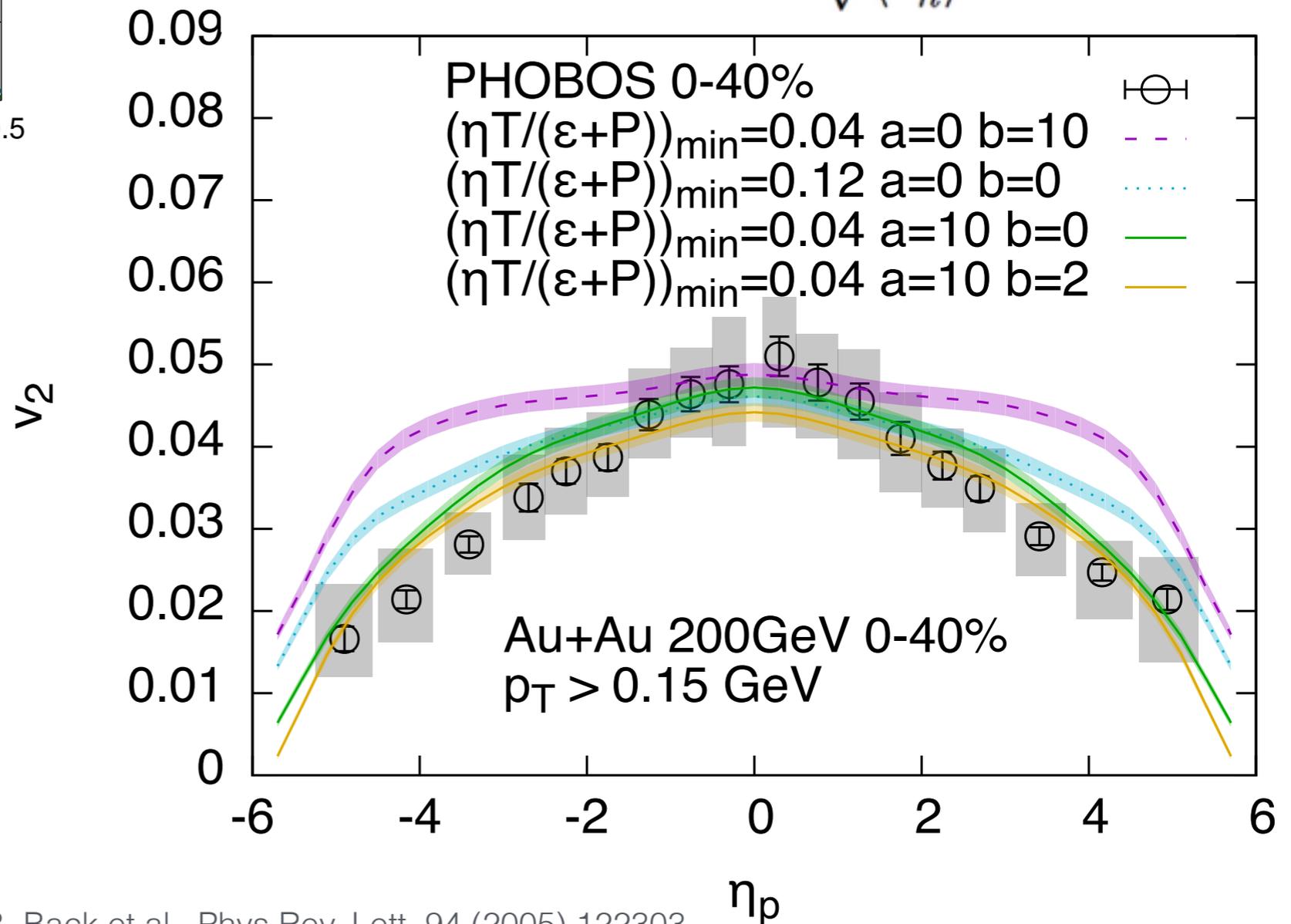
Experimental data: PHOBOS Collaboration, B. Alver et al., Phys. Rev. C83, 024913 (2011)

T dependent η/s from rapidity dependence

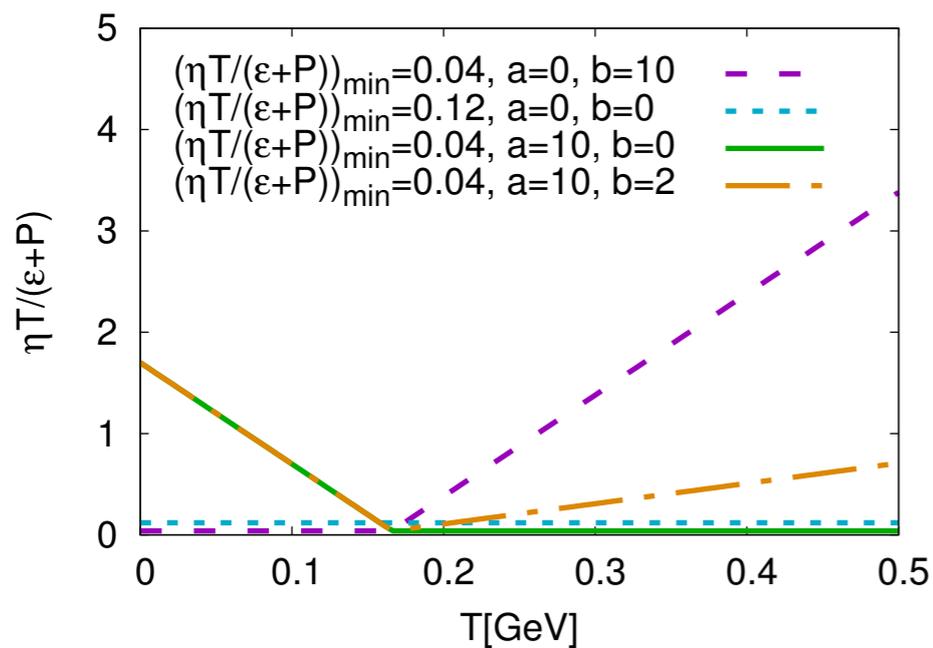


Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538

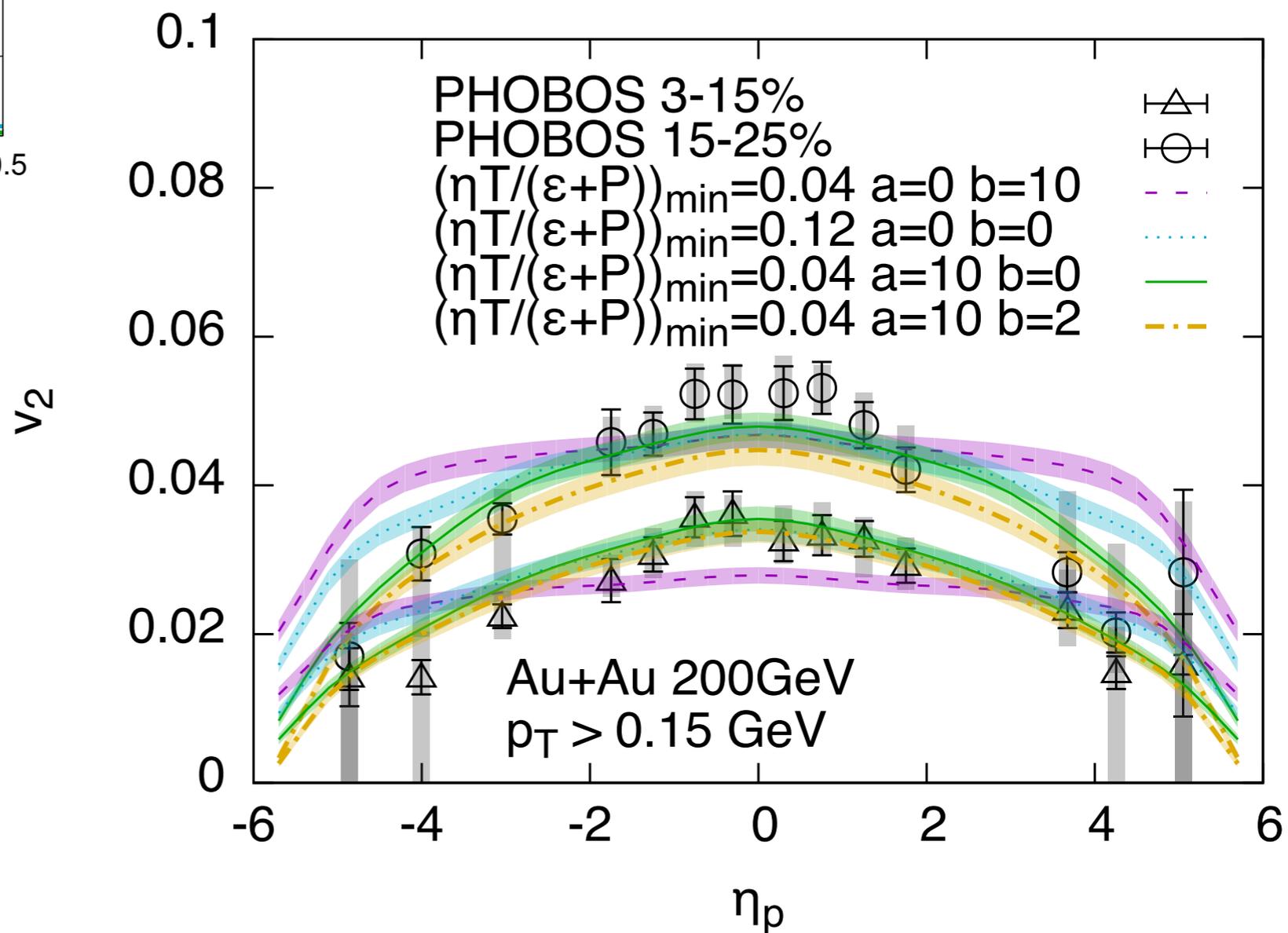
$$v_n\{2\}(\eta_p) = \frac{\langle v_n v_n(\eta_p) \cos[n(\psi_n - \psi_n(\eta_p))] \rangle}{\sqrt{\langle v_n^2 \rangle}}$$



T dependent η/s from rapidity dependence

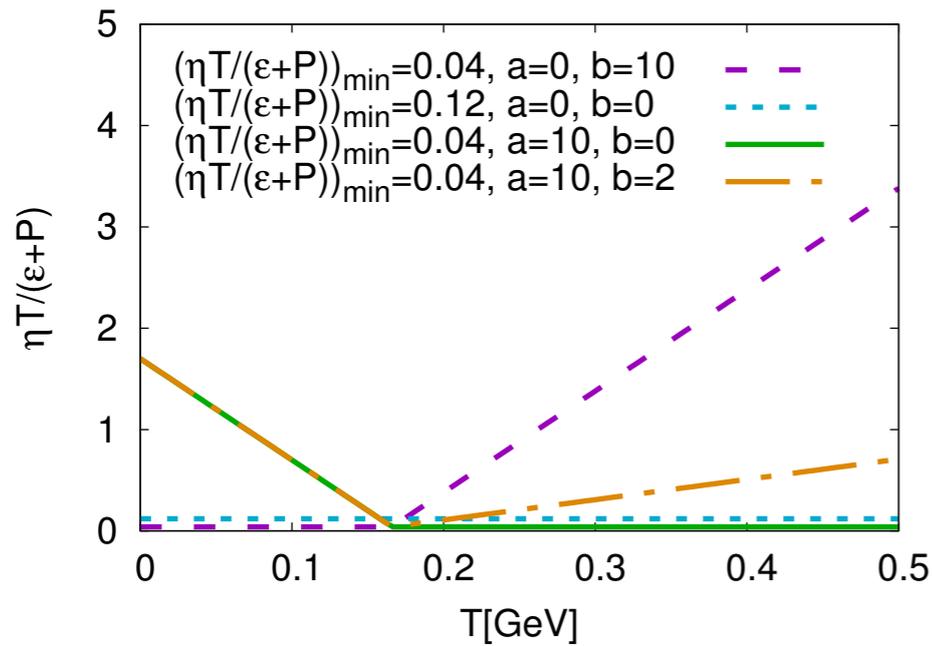


Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538

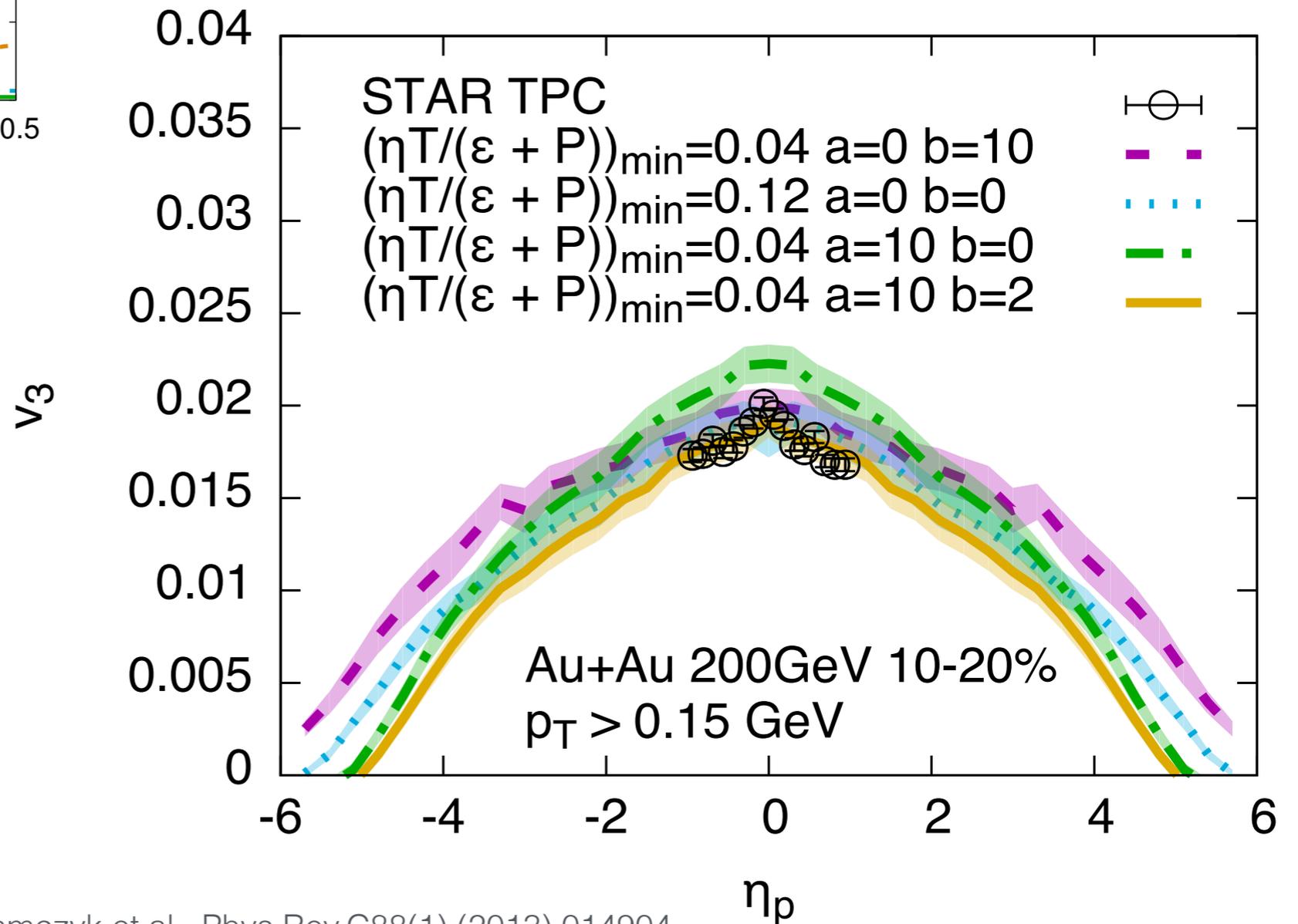


Experimental data: PHOBOS Collaboration, B.B. Back et al., Phys. Rev. C72, 051901 (2005)

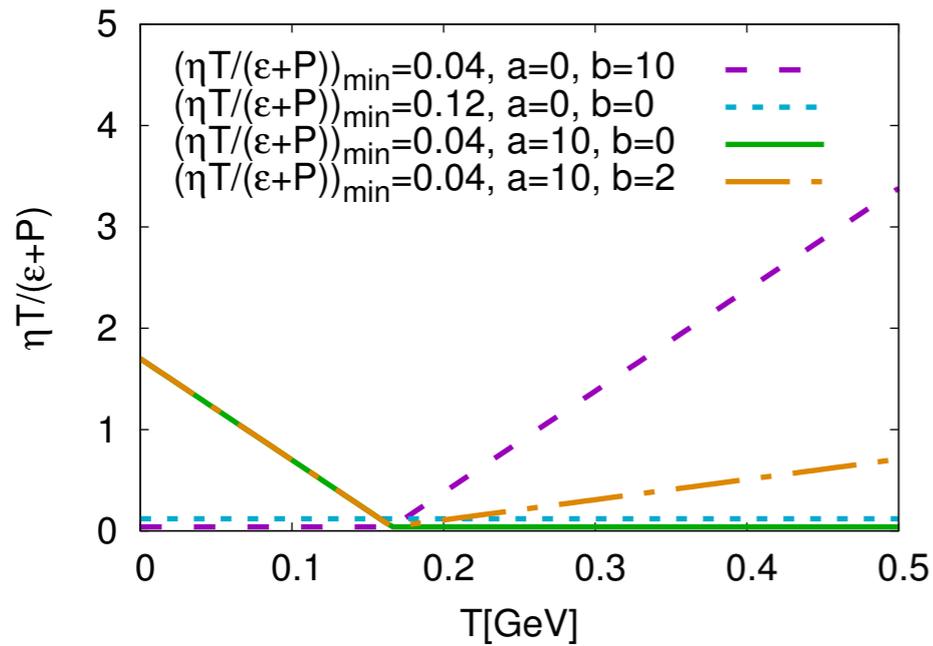
T dependent η/s from rapidity dependence



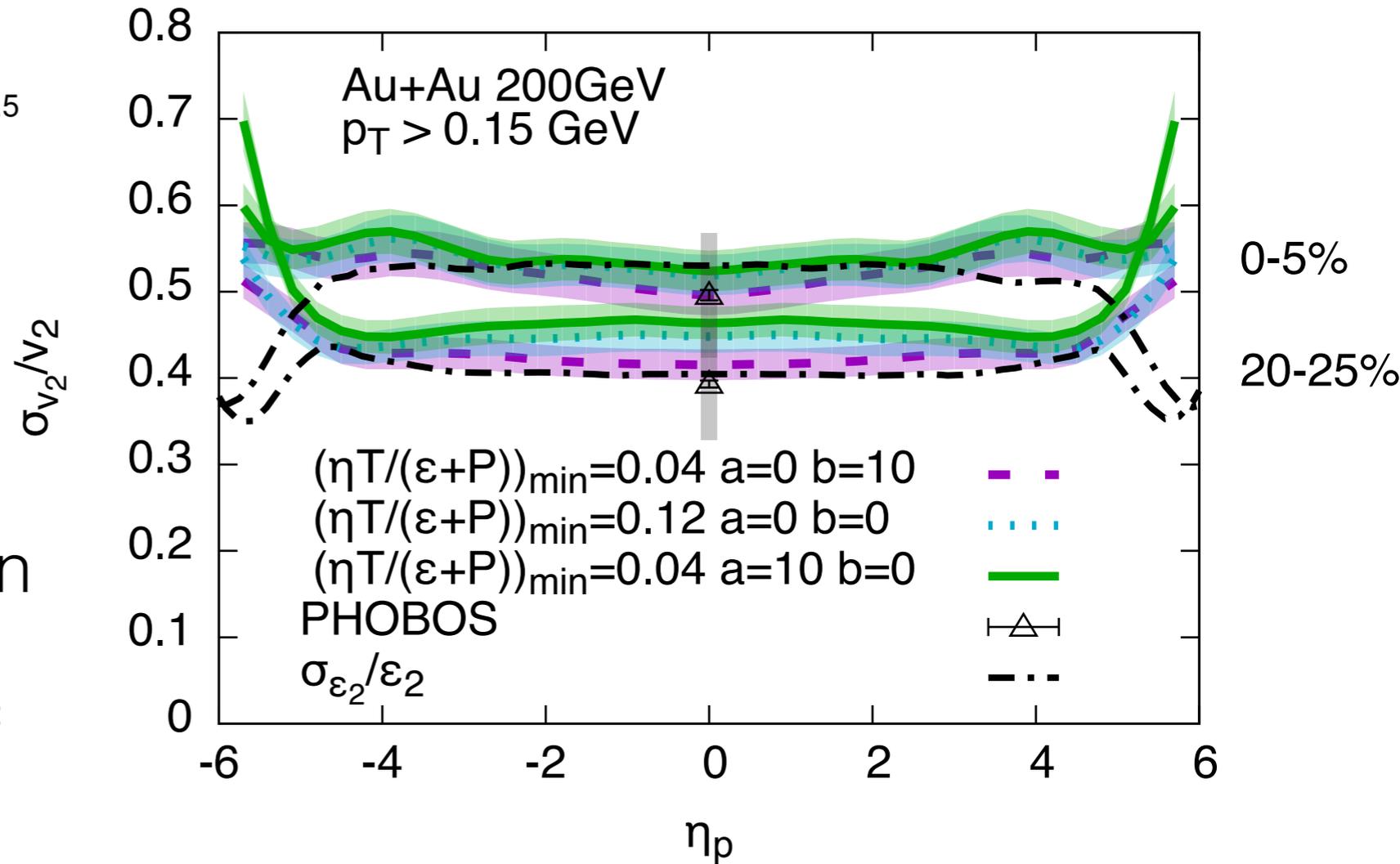
Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538
 Gabriel Denicol, Akihiko Monnai, Sangwook Ryu, Bjoern Schenke
 arXiv:1512.08231



v_2 fluctuations vs. pseudo-rapidity



Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, arXiv:1512.01538



- variance of the distribution
- 1) flat in pseudo-rapidity
 - 2) almost independent of transport properties

Two-particle pseudo-rapidity correlations

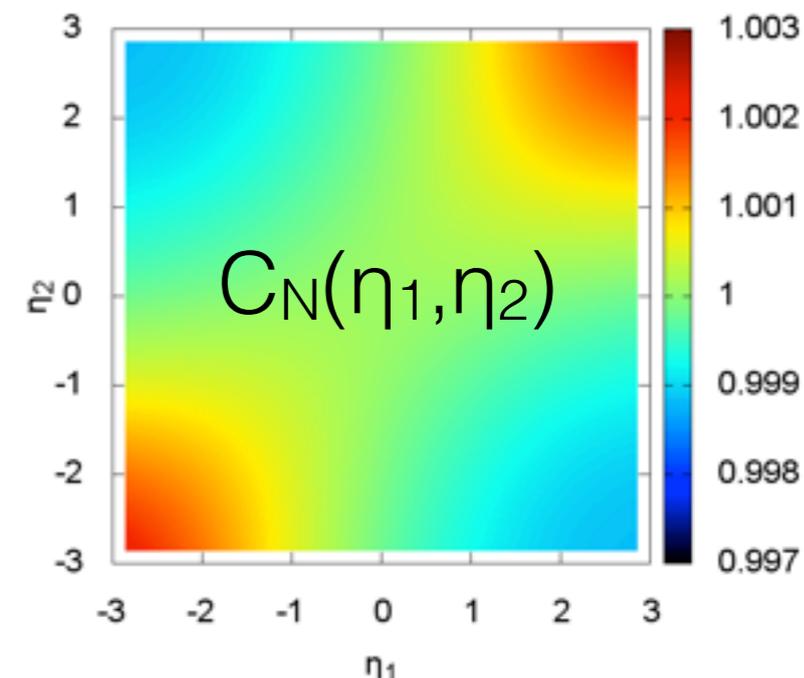
$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1)N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle}$$

to remove the effect of a residual centrality dependence in 5% bin

$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1)C_p(\eta_2)}$$

with

$$C_p(\eta_{1/2}) = \frac{1}{2Y} \int_{-Y}^Y C(\eta_1, \eta_2) d\eta_{2/1}$$

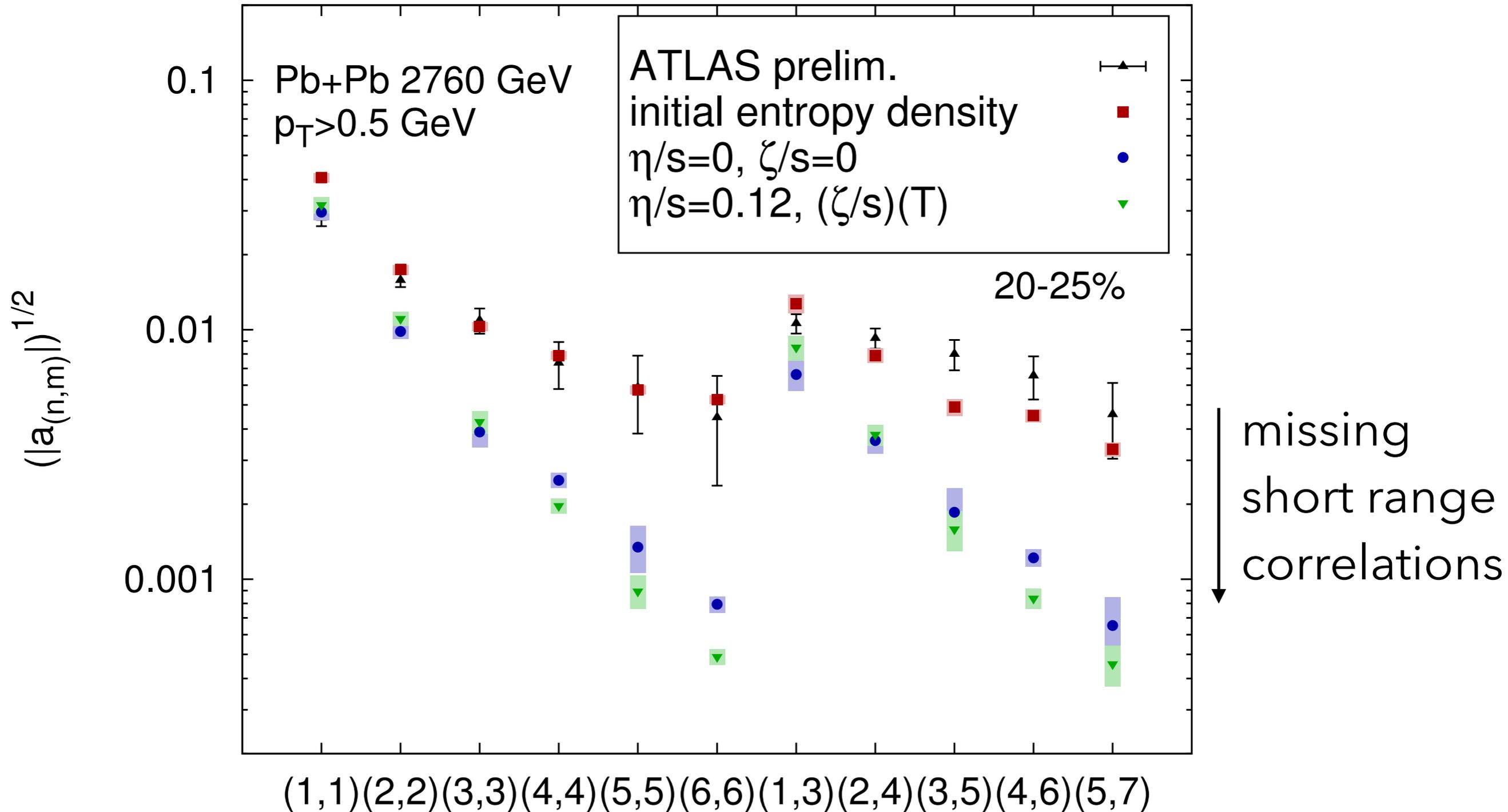


Expand in Legendre polynomials. The coefficients are given by

$$a_{n,m} = \int C_N(\eta_1, \eta_2) \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2} \frac{d\eta_1}{Y} \frac{d\eta_2}{Y}$$

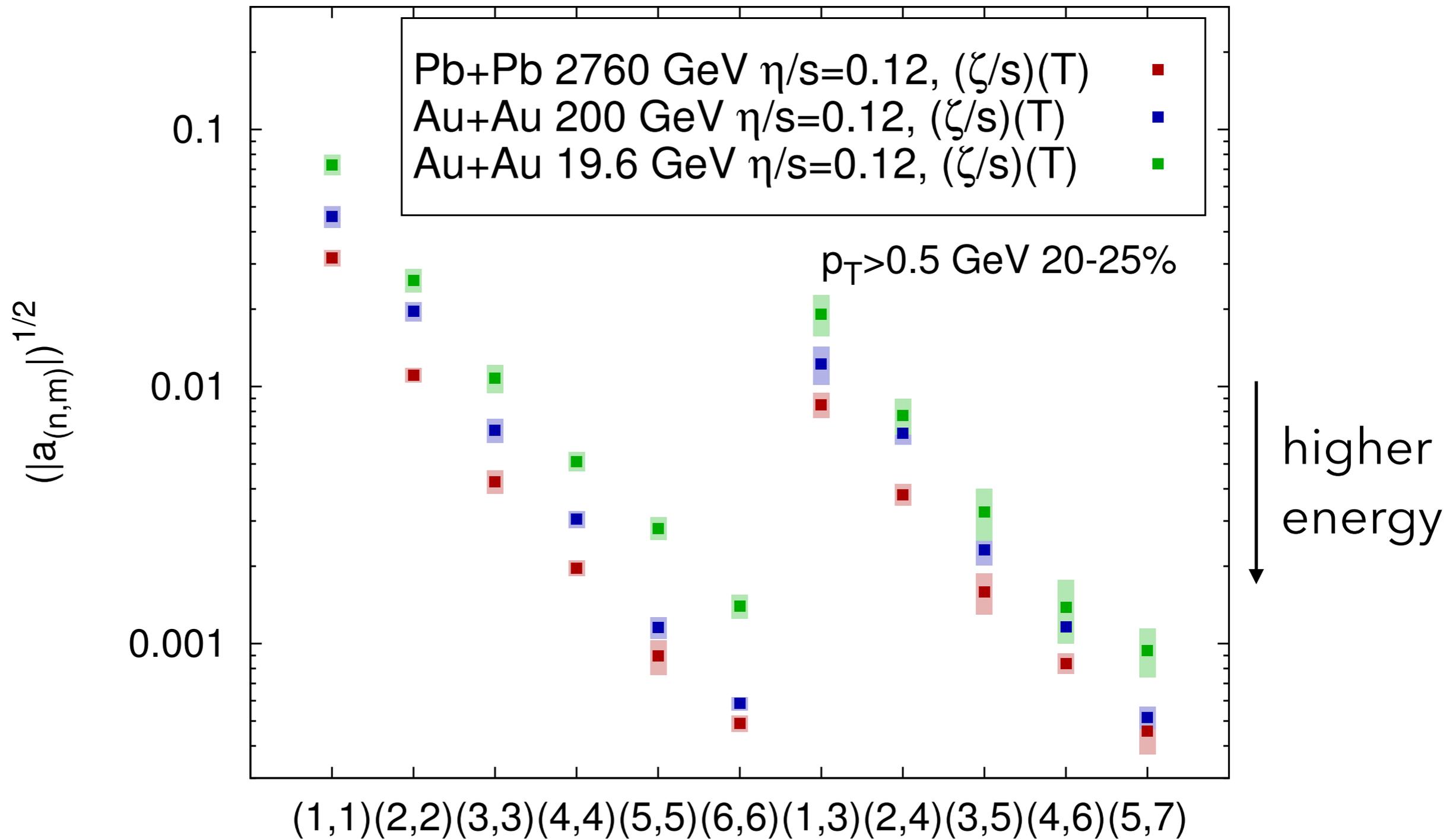
Two-particle pseudo-rapidity correlations

A. Monnai, B. Schenke, Phys. Lett. B752, 317-321 (2015)



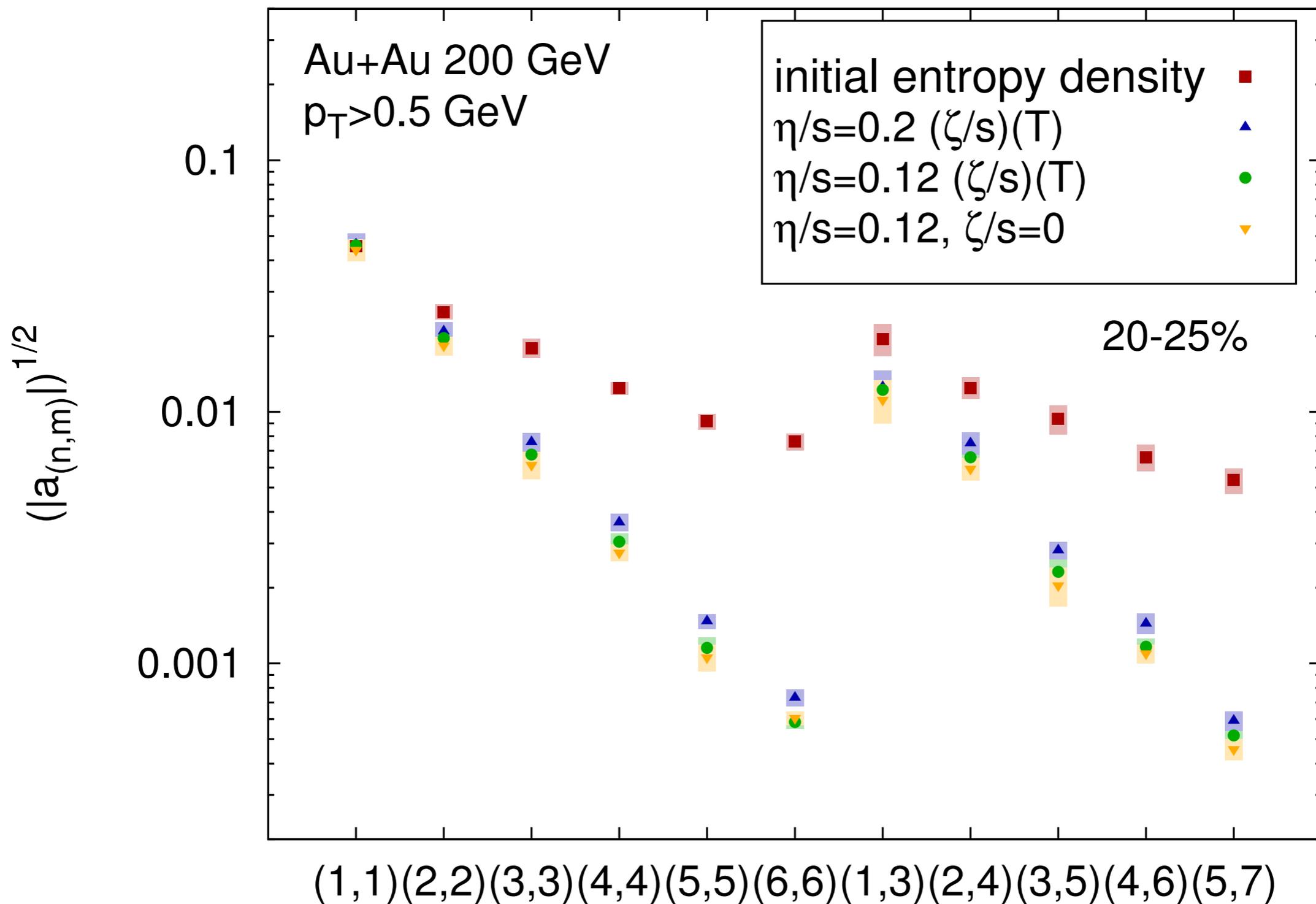
Collision energy dependence

A. Monnai, B. Schenke, Phys. Lett. B752, 317-321 (2015)



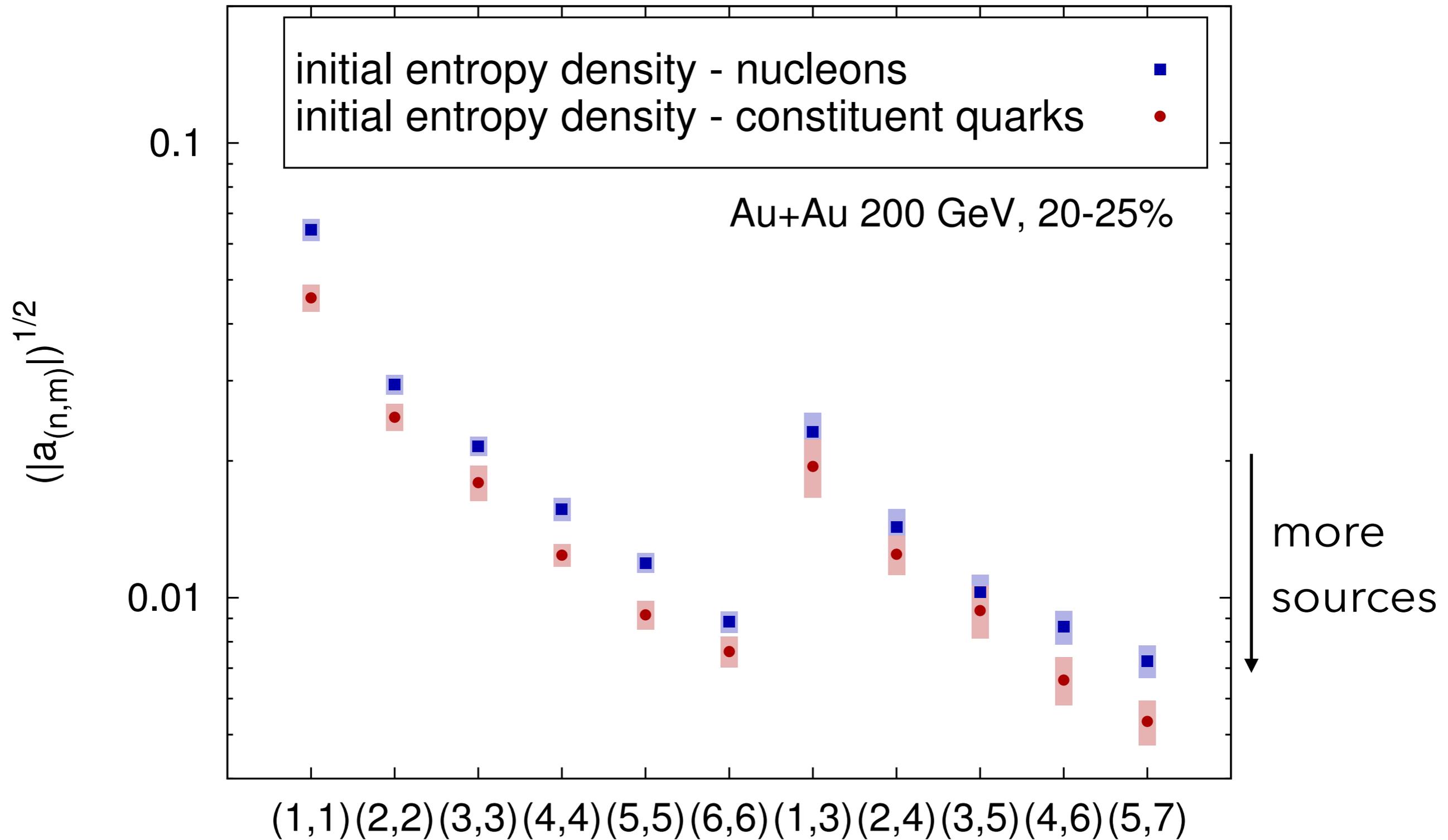
Effect of shear and bulk viscosity

A. Monnai, B. Schenke, Phys. Lett. B752, 317-321 (2015)



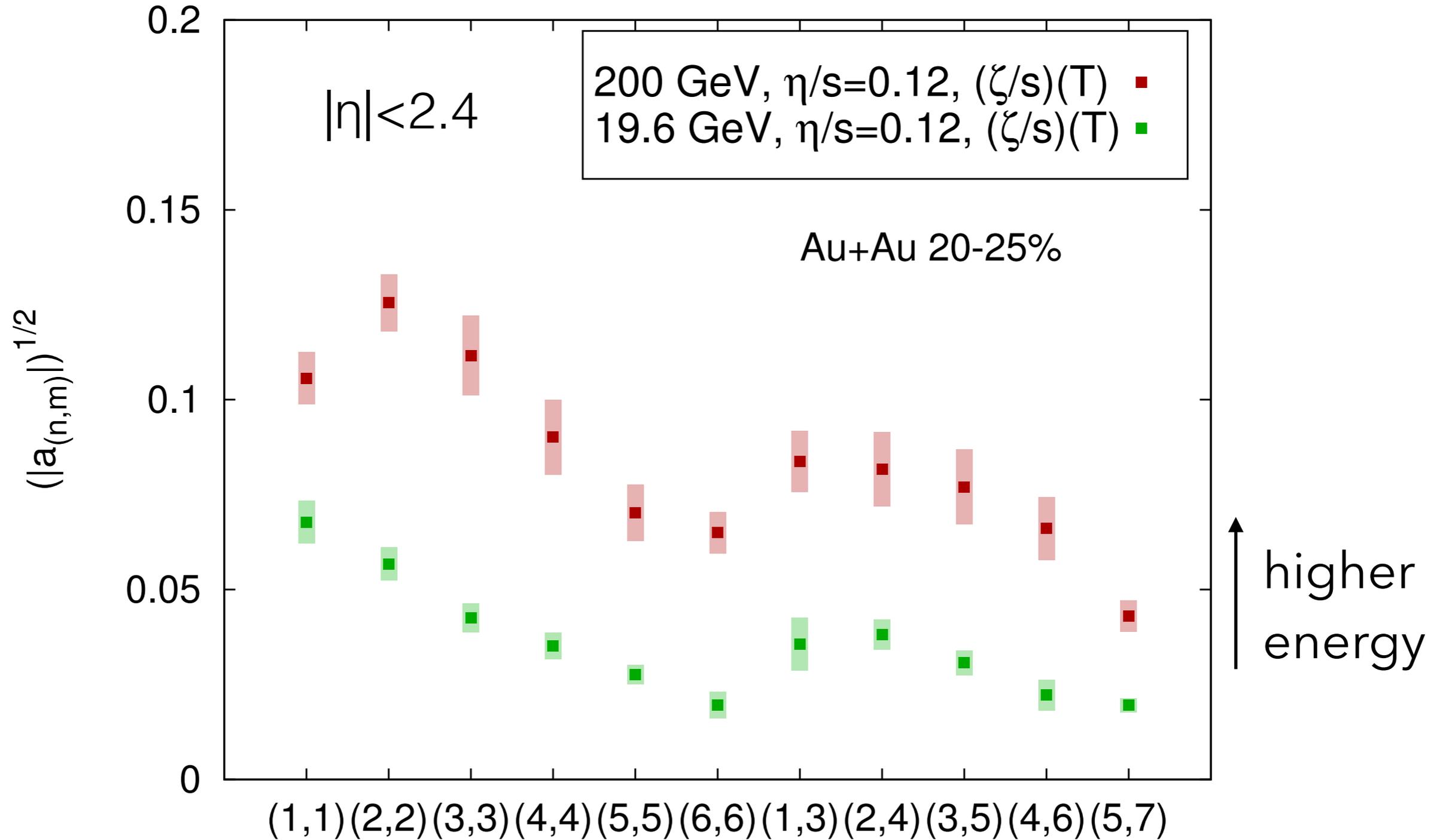
Effect of the number of sources

A. Monnai, B. Schenke, Phys. Lett. B752, 317-321 (2015)



Net baryon pseudo-rapidity correlations

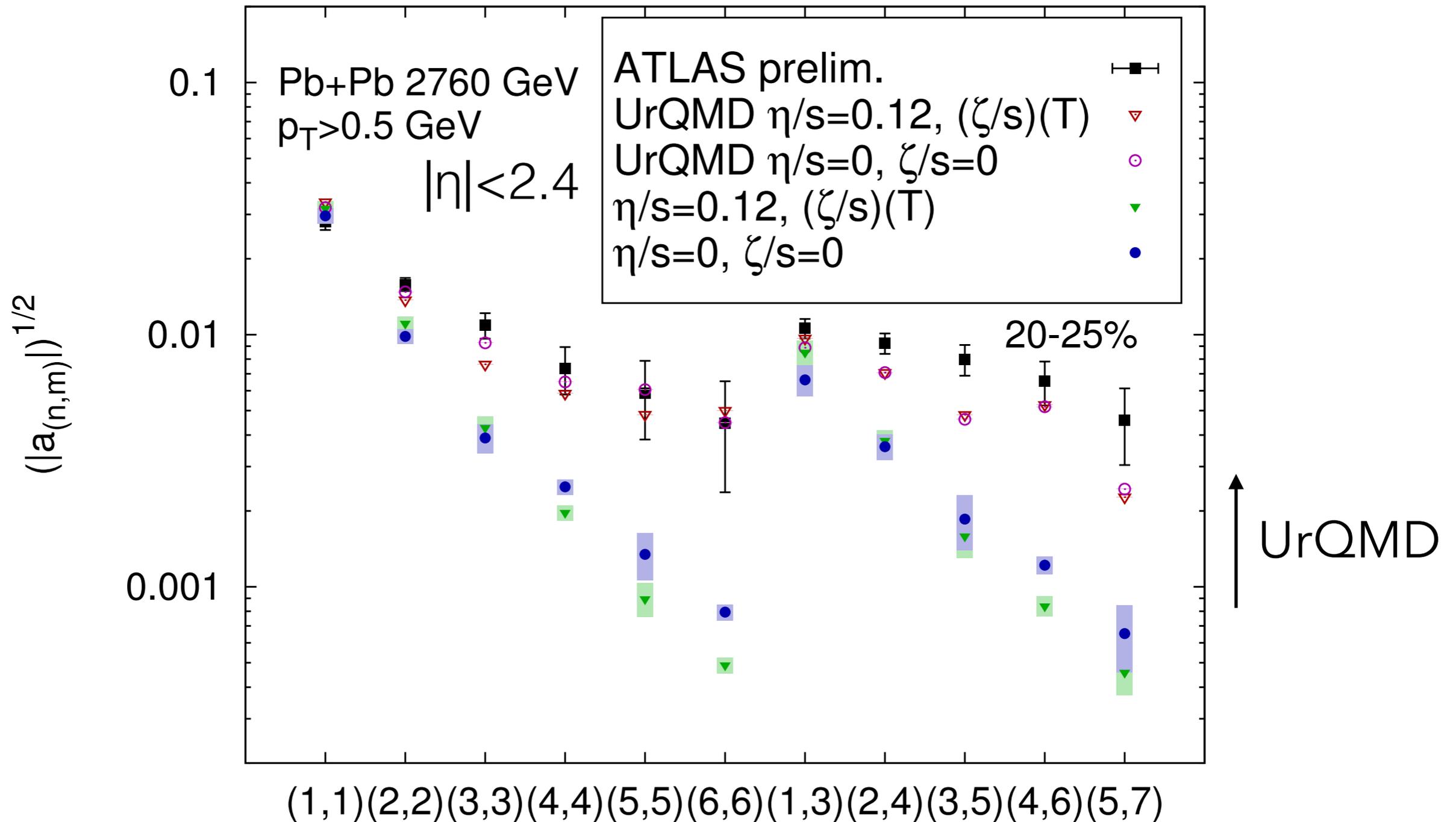
A. Monnai, B. Schenke, Phys. Lett. B752, 317-321 (2015)



Measure this: Could help our understanding of baryon stopping

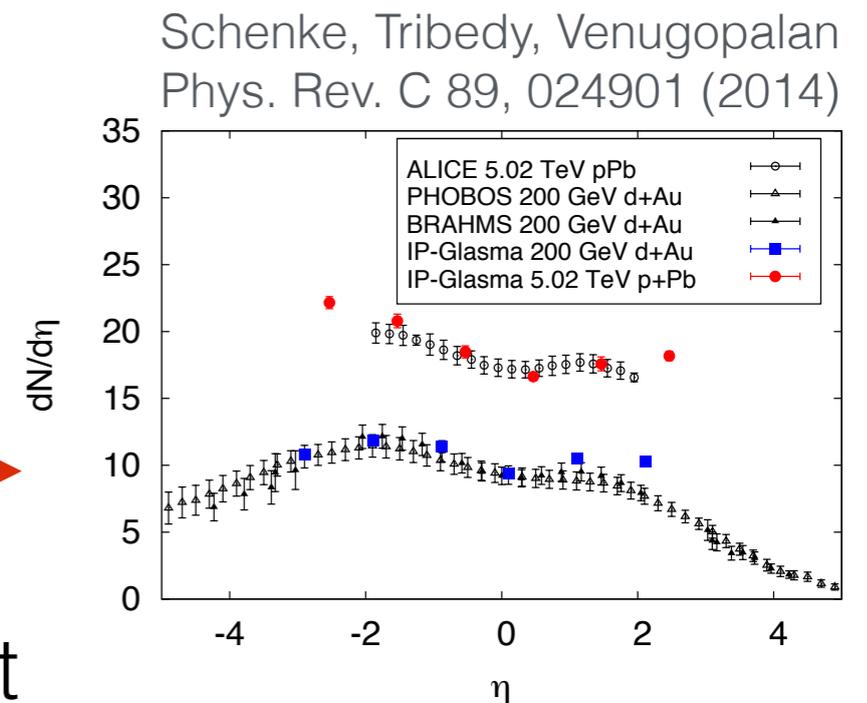
Couple to UrQMD: short range correlations matter

Gabriel Denicol, Akihiko Monnai, Sangwook Ryu, Bjoern Schenke, arXiv:1512.08231



IP-Glasma+JIMWLK

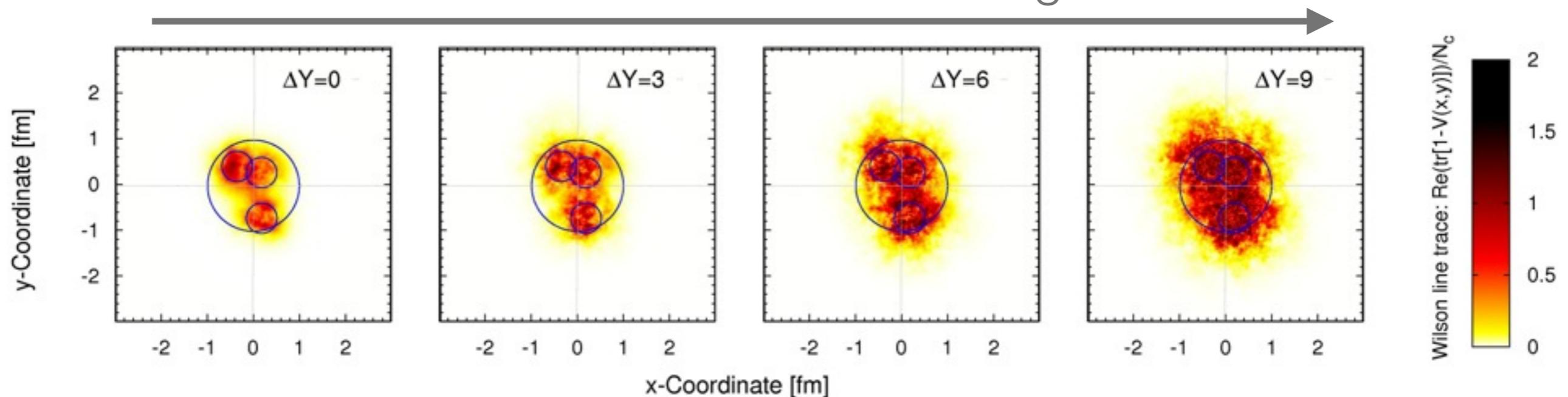
- IP-Glasma is boost invariant and uses a parametrization for the x dependence
- Changing the rapidity changes x , changes Q_s , changes the multiplicity \longrightarrow
- However, energy density in a single event is boost invariant - a full 3D Glasma calculation is very hard
- To do better we can replace the parametrization by JIMWLK
- Then compute energy density at different rapidities
- Will contain rapidity correlations via “geometry”
- Then combine all slices in rapidity to make 3D initial condition for hydrodynamics



IP-Glasma+JIMWLK

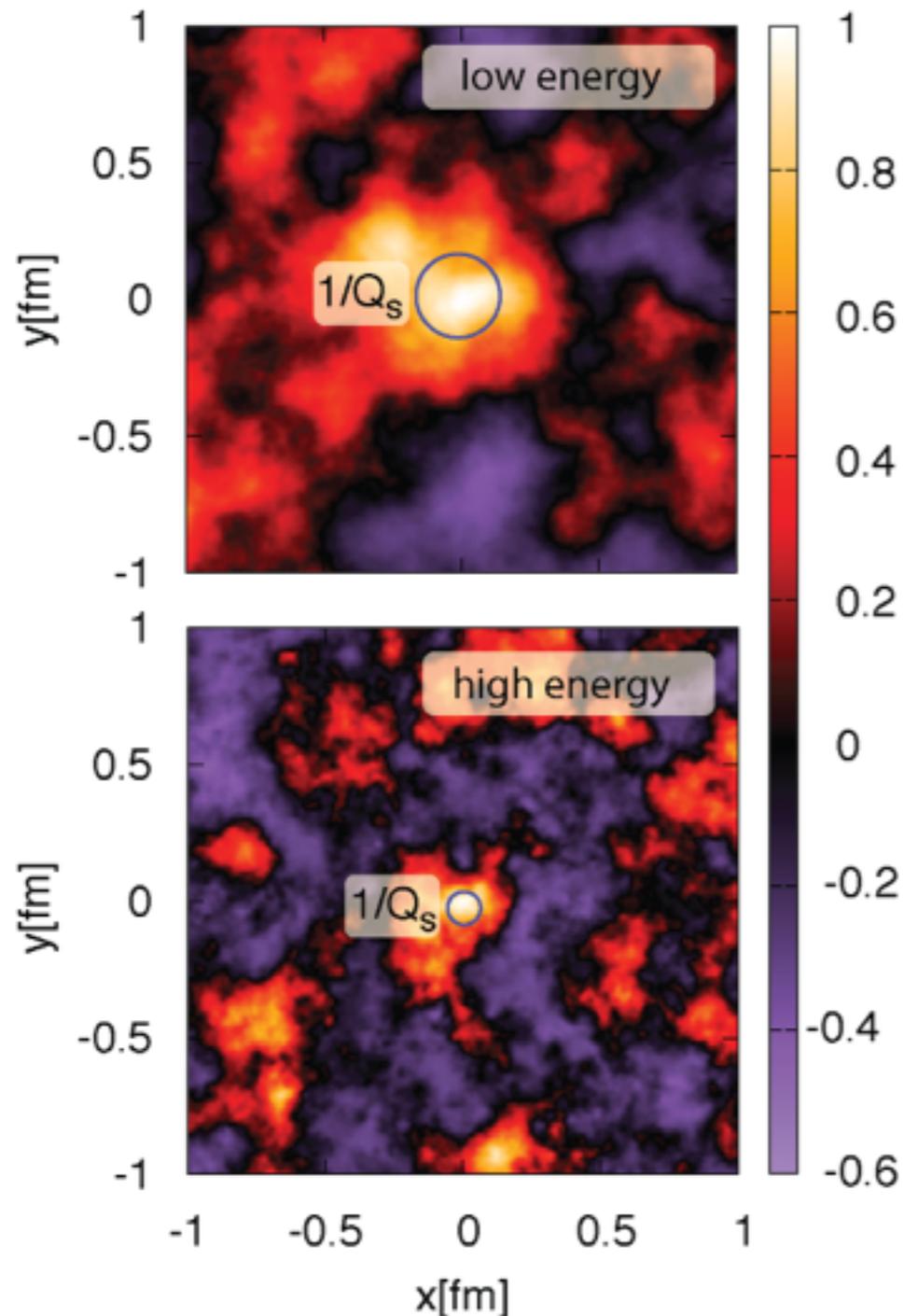
- Then combine all slices in rapidity to make 3D initial condition for hydrodynamics
- *What needs to be done before all that:*
Constrain parameters (in particular running coupling) in JIMWLK-Glasma calculation using DIS data just like in IP-Glasma

JIMWLK evolution: decreasing x



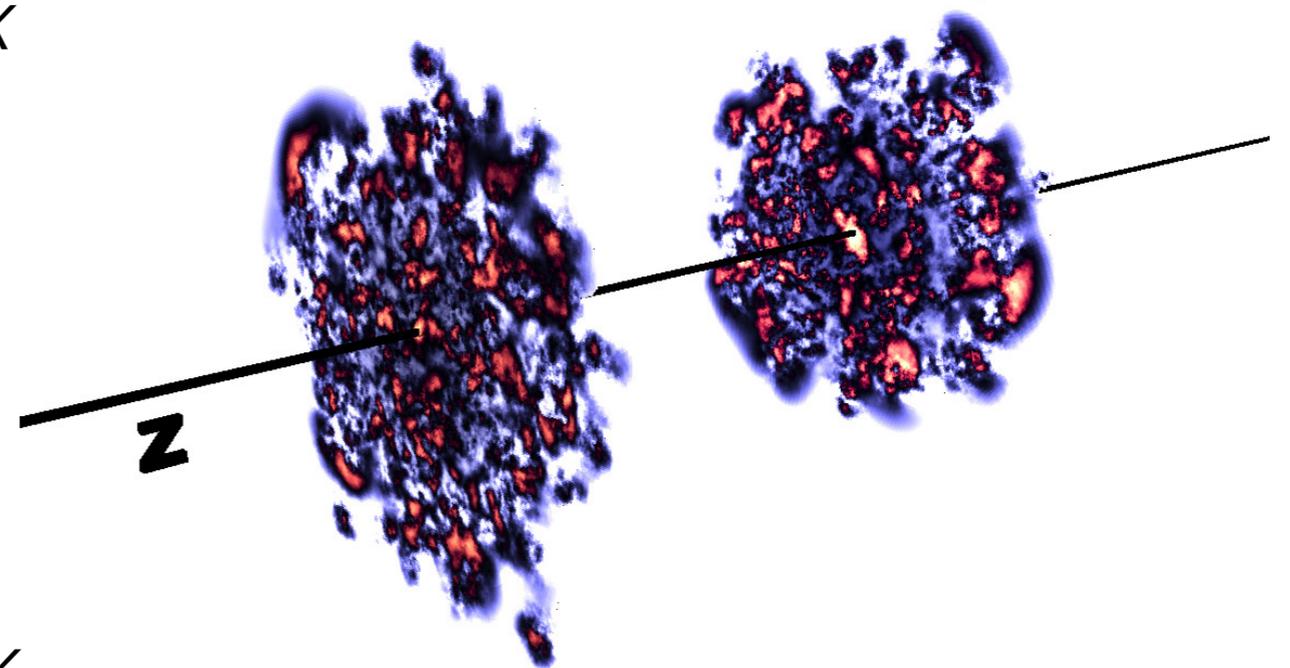
JIMWLK: Correlation length within one nucleus

A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke, R. Venugopalan, Phys. Lett. B706, 219-224 (2011)



large x

small x



At forward rapidity one should be sensitive (multi-particle correlations?) to the change in transverse structure of the two nuclei

Conclusions

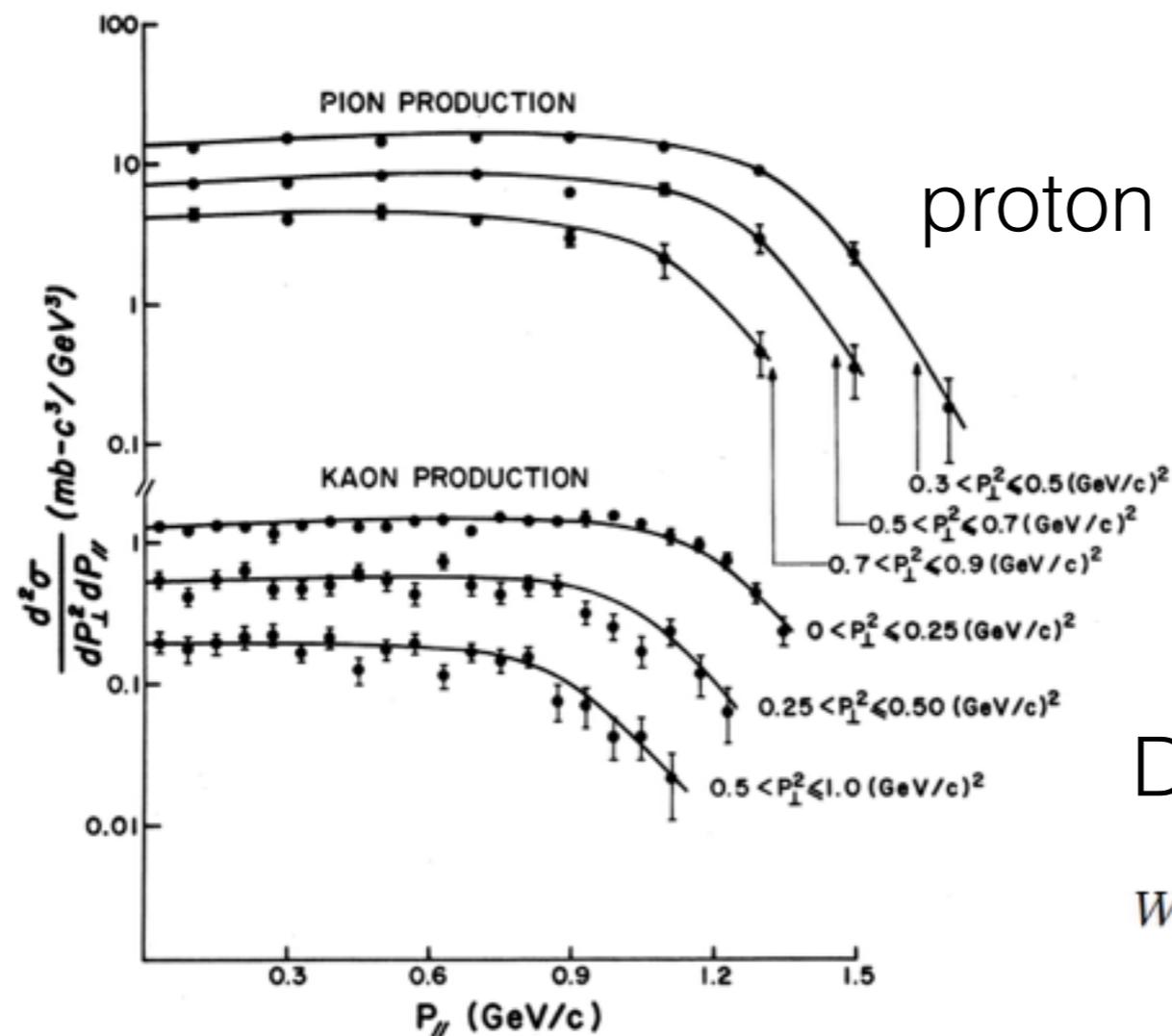
- 3+1D viscous relativistic fluid dynamics with fluctuations of baryon number and entropy density in all three dimensions
- Rapidity and energy dependence of flow harmonics contains information on transport coefficients' T and μ_B dependence
- Two particle rapidity correlations contain information on the number of sources; are sensitive to short range correlations
- Net-baryon rapidity correlations can shed more light on baryon stopping: Measure them!
- Outlook: Redo with CGC initial state - Measurements at different energy and rapidities will be able to scan through the various combinations of Q_s that affect the fluctuating structure

Backup

Lexus model S. Jeon and J. Kapusta, PRC56, 468 (1997)

Input: The distribution of outgoing nucleons in a high energy nucleon-nucleon collision is flat in longitudinal momentum or a hyperbolic cosine (symmetric about the CM) in rapidity

M. A. Abolins, G. A. Smith, Z. Ming Ma, Eugene Gellert, and A. B. Wicklund
Phys. Rev. Lett. 25, 126



proton long. momentum distributions

Distribution of outgoing projectile

$$W_{11}^P(y) = Q(y, y_0, y_0 - y) = \lambda \frac{\cosh y}{\sinh y_0} + (1 - \lambda) \delta(y_0 - y)$$

FIG. 1. Proton c.m. longitudinal-momentum distributions for various values of P_{\perp}^2 . The solid lines are free-hand fits to the data.

δf corrections in the presence of net baryons

A. Monnai, T. Hirano, PRC80, 054906 (2009); Nucl. Phys. A847, 283 (2010)

Grad's 14 moment method

$$\delta f^i = -f_0^i (1 \pm f_0^i) (b_i \varepsilon_{\mu}^B p_i^{\mu} + \varepsilon_{\mu\nu} p_i^{\mu} p_i^{\nu})$$



particle i 's baryon quantum number

ε_{μ}^B and $\varepsilon_{\mu\nu}$ are determined by the self-consistency conditions

$$\delta T^{\mu\nu} = \sum_i \int \frac{g_i d^3 p}{(2\pi)^3 E_i} p_i^{\mu} p_i^{\nu} \delta f^i = -\Pi \Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\delta N_B^{\mu} = \sum_i \int \frac{b_i g_i d^3 p}{(2\pi)^3 E_i} p_i^{\mu} p_i^{\nu} \delta f^i = \cancel{V_B^{\mu}} = 0 \quad (\text{no baryon diffusion})$$

δf corrections in the presence of net baryons

A. Monnai, T. Hirano, PRC80, 054906 (2009); Nucl. Phys. A847, 283 (2010)

Grad's 14 moment method

$$\delta f^i = -f_0^i (1 \pm f_0^i) (b_i \varepsilon_\mu^B p_i^\mu + \varepsilon_{\mu\nu} p_i^\mu p_i^\nu)$$

After tensor decomposition and one finds

$$\varepsilon_\mu^B = D_\Pi \Pi u_\mu$$

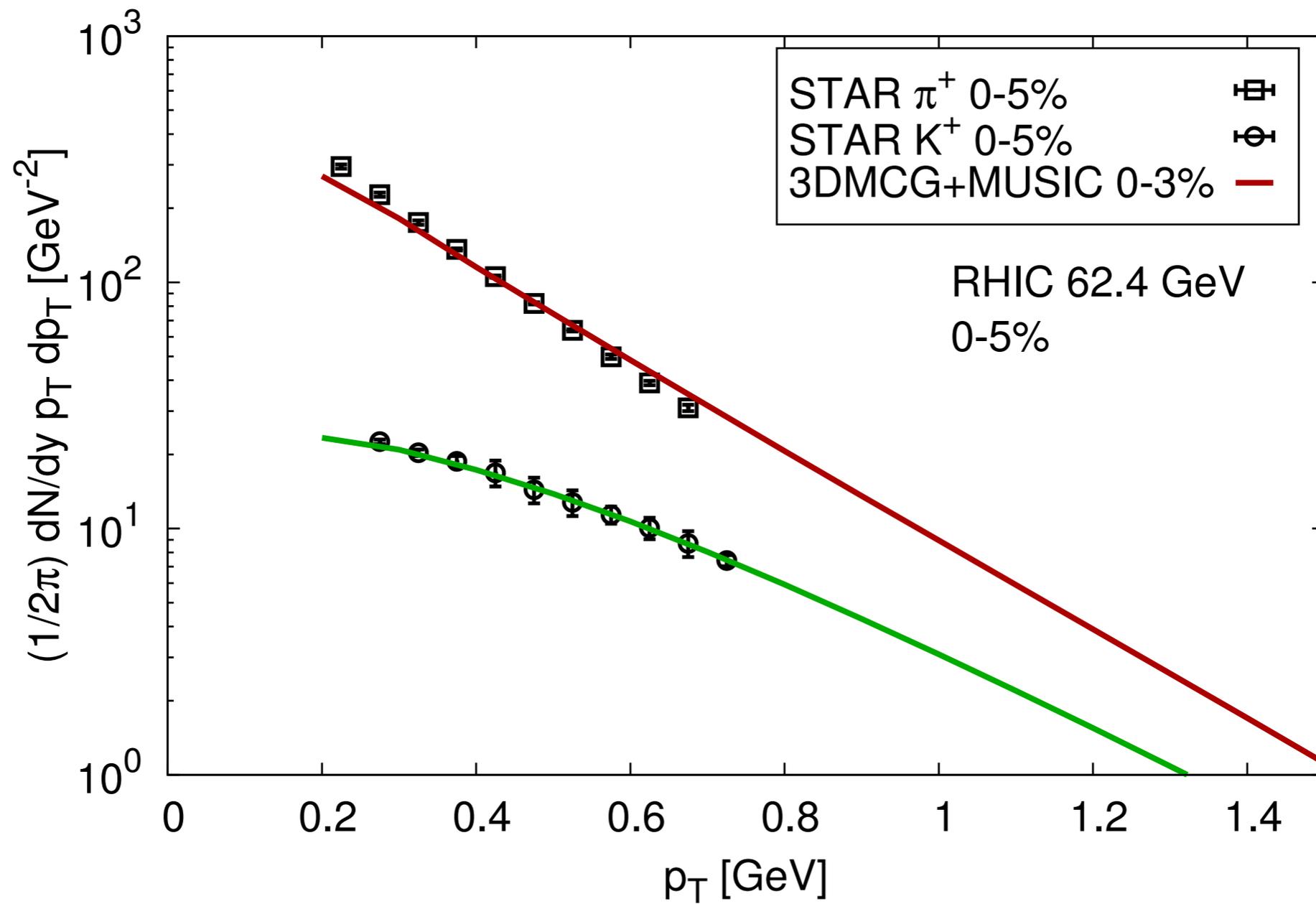
$$\varepsilon_{\mu\nu} = (B_\Pi \Delta_{\mu\nu} + \tilde{B}_\Pi u_\mu u_\nu) \Pi + B_\pi \pi_{\mu\nu}$$

where the coefficients are computed in kinetic theory

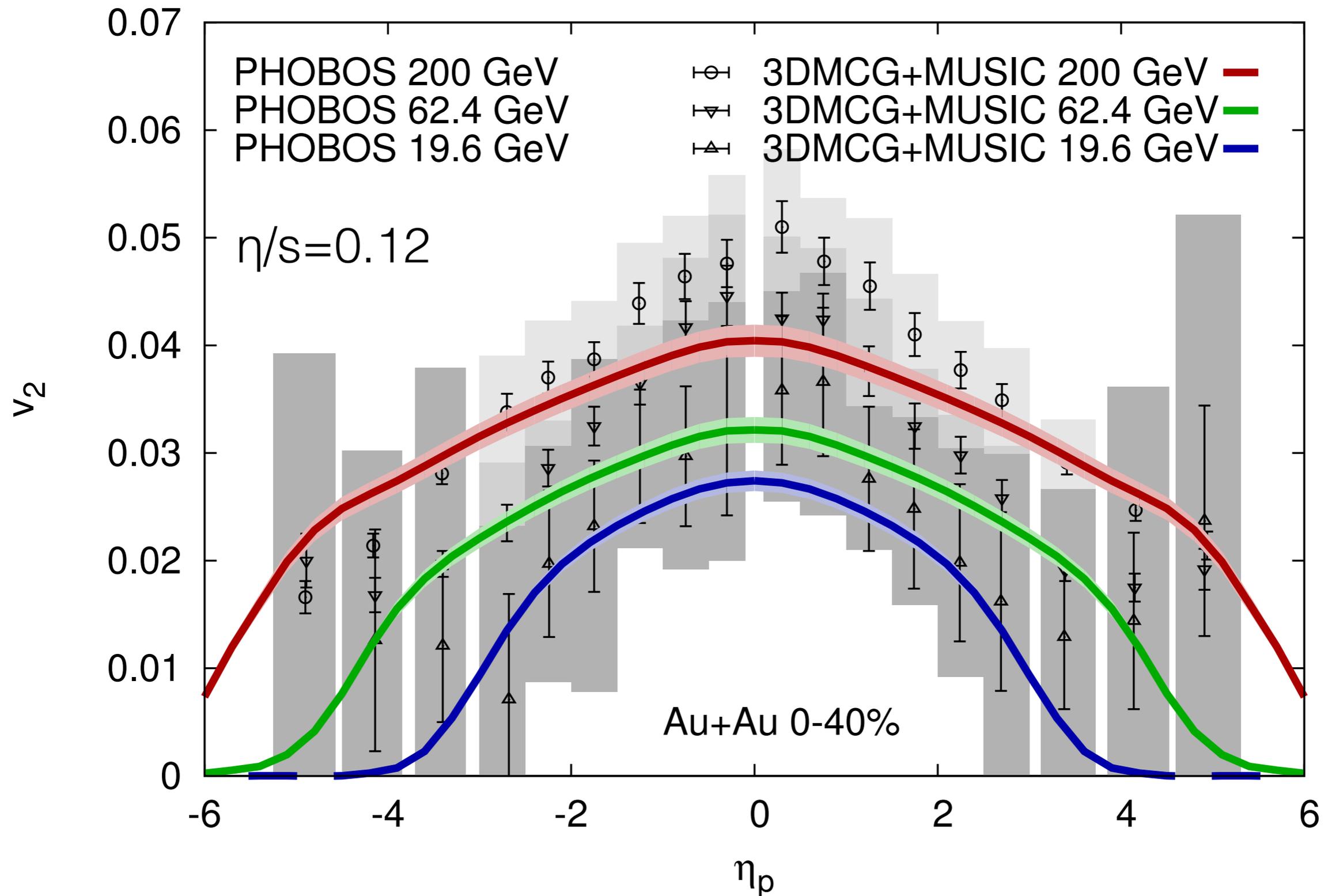
We parametrize them as functions of T and μ_B

Note: Results of net baryon density are very sensitive to accuracy of the bulk- δf parametrization

Transverse momentum spectra at 62.4 GeV



v_2 vs pseudo-rapidity at different energies



Two-particle pseudo-rapidity correlations

A. Monnai, B. Schenke, arXiv:1509.04103

